Chapter 11
Electronic Tongue for Food Safety and Quality Assessment

Farrhin Nowshad and Mohidus Samad Khan

Abstract The sense of smell and taste play a fundamental role in human development and biosocial interactions. Taste is an important organoleptic property governing the assessment of food products. It is one of the prime factors determining the quality, market potential, and commercial success of foods. Thus, taste assessment is one of the most important quality control parameters for evaluating foods. The primary subjective method for taste measurement is generally by human panelists. However, the sensory method is very complicated to perform and analyze; it is variable depending on the panelists and conditions of assessment. In addition, it is time-consuming and thus difficult to include in the quality assessment in the food production line. Recruiting taste panelists and maintaining them can be highly difficult, especially when working with food products not preferred by the panelists. Furthermore, unsafe and toxic molecules are not allowed to be tested by the sensory method. Therefore, the analytical taste-sensing multichannel sensory system called as electronic tongue (also known as e-tongue or artificial tongue) could replace the sensory panelists. The concept of the electronic tongue is to measure a "fingerprint" of a sample allowing sensitive comparison in relation to the taste measurements. A sound basis for electronic tongues is provided by the extensive progress of developing well-known selective sensors, especially electrochemical and biological mimicking sensory systems of mammalians. The electronic tongue can be used for a wide range of food items to characterize, authenticate, quality evaluation, process monitoring, and quantitative analysis of foods. Thus, electronic tongue includes benefits like reducing reliance on human panel, and it could be rapid and used in the quality control in the food production line. This article briefly discusses the mechanism and application of electronic tongue with respect to food safety and quality assessment, and the contents would be highly useful to the food professionals working in the academic, research, and industry.

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1 Introduction

Determining the quality of foods is critical to the consumers. Quality of food can often be associated with taste since undesired taste often indicates degradation of foods. The relationship among taste, flavor, and consumer preference is the key to retain and increase customer satisfaction. However, we are inherently varied by our inability to assess food quality considering smell, sight, sound, touch, and taste [1]. There are various types of analytical methods that can provide information about physical and chemical characteristics of foods. However, these methods are often complicated and time-consuming. For processing and quality control, the food industry generally requires methods that are simple, rapid, and able to provide reliable data about foods. Therefore, there is a high need to develop rapid and low-cost methods to measure attributes related to the sensory taste of different foods.

Taste sensation in humans arises through physicochemical interactions of selected molecules present in food and complex system of cell buds located on the tongue [1]. The sense of taste includes sourness, saltiness, bitterness, sweetness, and umami [2]. We perceive each type of taste attribute during food consumption. Taste buds are composed of approximately 50–100 taste cells [2]. Each taste cell has receptors, which bind to the molecules and ions and the result is the taste sensations [3]. Taste information perceived by taste buds is transmitted to taste nerves through neurotransmitters, and finally, the signal reaches the gustatory area in the brain [2]. In brief, taste formation is related to chemical transduction in the papillae of the human tongue with activation of intrinsic and extrinsic neuronal circuits. It is mediated by regulatory membrane receptors through a complex network [4–7]. According to the Classical Threshold Theory, taste sensations depend on the intensity of the attributes of the stimulus. Stimulus is perceived only when its intensity is above a specific level or threshold [4]. Scale descriptors and/or geometric mean values are normally used in human tasting panels [6], and it is not easy to assign a scale or unit for measuring taste. Therefore, it can be said that taste is identified through a combination of nonspecific responses obtained by a series of nonspecific molecular recognition events [8]. The pattern created by the simultaneous response of these receptors is specific for a particular set of stimuli [1]. Unfortunately, the inherent variability of the receptor density over the tongue and palate causes the differences between human to human perceptions of taste. Therefore, even if members of a taste panel are well trained and calibrated, the evaluation still remains subjective. Therefore, it is still troublesome in some industrial applications. For this reason, researchers and management associated with food, beverage, and pharmaceutical industries have been seeking a reliable, low-cost, reproducible analytical tool to analyze the taste of foods.

The term E-tongue was coined owing to the similarity with the human gustatory system, which is based on the concept of global selectivity [9–11]. The electronic tongue systems are designed as an array of non-specific and low selective chemical sensors with partial specificity (cross-sensitivity) to different components present in the sample under investigation [1]. The electronic tongue consists of an array of liquid sensors with a different selectivity, a signal collecting unit, and a pattern recognition software [12]. When exposed to a sample containing different compounds, it generates an output pattern representing a combination of all the components in the sample. The output pattern is given by different selectivity and sensitivity of individual sensing units and is correlated with a specific taste or quality aspect [13]. The sensors of electronic tongue "taste" raw substances, semi-products, and finished products in a fast and nondestructive method; hence, the electronic tongue could contribute to improve automation of food processes. Electronic tongue techniques can also be used in food classification, freshness evaluation, authenticity assessment, and quality control [1]. E-tongue has thus emerged as a very capable, rapid, and easy-to-use tool for evaluation of food quality [14]. In addition, they have also been widely used in the monitoring of environmental conditions, medical diagnostics, detection of herbal products, and detection of endotoxins and pesticides in different products [13].

In this chapter, a brief portrayal of the development of the electronic tongue is included along with different types of sensors used in electronic tongue systems. Applications described in this chapter include process monitoring, freshness evaluation, authenticity assessment, foodstuff recognition, quantitative analysis of foods, and food safety assessment. Finally, future directions, strengths, and weaknesses of electronic tongues are also mentioned.

2 Electronic Tongue in Food Analysis and Its Other Applications

Food analysis has become a very important area of research due to the fast growth of the food trade and increasing awareness of food safety [15]. Food analysis provides information about different characteristics of foods, including their composition, structure, physicochemical properties, and sensory attributes [15]. This information is critical to our rational understanding of the factors that determine the properties of foods as well as to our ability to economically produce foods that are consistently safe, nutritious, and desirable. One of the most important reasons for analyzing foods is to ensure that they are safe. In food analysis, a wide range of traditional methodologies such as liquid chromatography, IR, and UV spectroscopy are used to determine or detect characteristics compounds in foods [14, 16]. These methodologies show good precision, accuracy, and reliability [14]. However, they are destructive, time-consuming, complex, require specialized personnel and extensive instrumentations, and inconvenient for in situ or at site monitoring [12, 14]. Electronic tongues can be used to overcome these drawbacks, and it could be very promising and easy-to-use tools for the evaluation of food quality [14]. Electronic

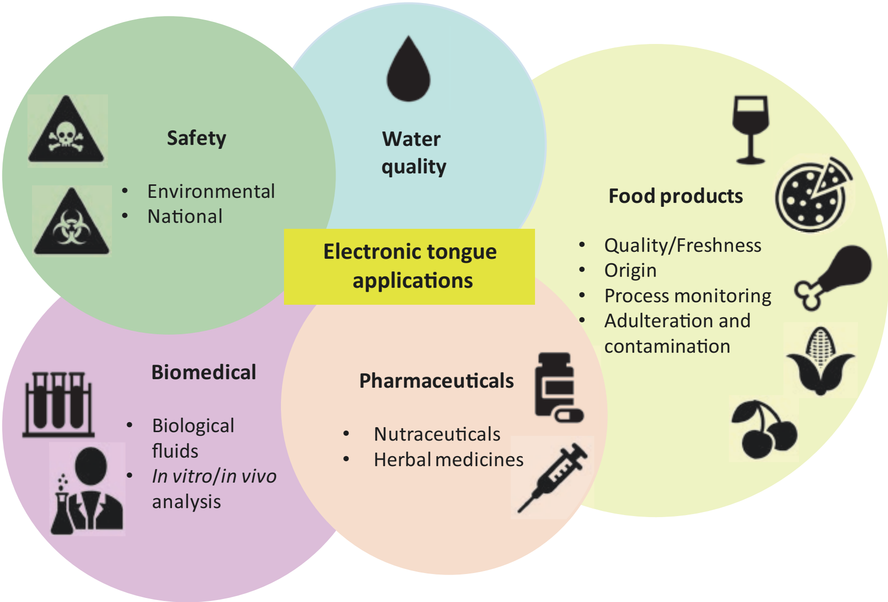

Fig. 11.1 Fields of application for electronic tongue systems. E-tongues are widely used for identifying hazardous and toxic chemicals, assessing water quality, ensuring food safety and in biomedical research and pharmaceutical industry

tongues can be highly useful for their rapid analysis and online capabilities to meet the trends of automation and continuous processing in the food industry [12]. This device is frequently used for the recognition, classification, and quantitative determination of multiple component concentrations [14].

Electronic tongues can be used for the detection of all types of dissolved compounds, including volatile compounds (i.e., odors) if dissolved in the solution [16]. Electronic tongues have already been used for the determination of fruit juice, onions, soft drinks, tea and herbal products, beverages, apples, milk, tomatoes, alcohol, coffee, sake, olive oil, beer, rice, cork, meat, and soya paste. However, electronic tongues are now also being used for environmental monitoring, water quality analysis, pesticide detection, medical diagnostics, and analyzing the fermentation process [17]. Figure 11.1 summarizes the versatile fields where E-tongue system is being used extensively.

3 Development of Electronic Tongue System

Electronic tongues have been developed based on the human taste mechanism. The human tongue is a mass of interlacing skeletal muscle, connective tissue with some mucous and serous glands, and pockets of adipose tissue, covered in oral mucosa

[18]. The mucosa covering the upper surface of the tongue is thrown into numerous tiny projections called the *papillae* [18]. Several thousands of taste buds are present on the surfaces of the papillae which are the collections of taste cells that connect to nerves running into the brain. In human gustatory system, the taste-producing substances are received by the biological membrane of gustatory cells in non-specific taste buds on the tongue [19–21]. The taste buds are chemoreceptors; they transduce or translate chemical signals in food into electrical signals in the body called action potentials, which travel to the brain through the nervous system allowing the sensation of taste [22]. In an E-tongue, the output of the nonspecific sensor array shows different patterns for the different taste-causing chemical substances, and such data are statistically processed [21].

3.1 General Mechanism of Electronic Tongue

The electronic tongue can be defined as "a multisensory system" for liquid analysis based on the combination of signals from non-specific and overlapping chemical sensors with suitable pattern recognition routines [1, 21]. The whole system of an e-tongue imitates what is happening when molecules with a specific taste nature interact with taste buds on the human tongue. The taste buds are represented by sensors that interact with these molecules at the surface initiating changes in potential. These signals are compared to physiological action potentials that are recorded by computer, which correspond to the neural network at the physiological level. Depending on the objective, the data obtained can further be evaluated on the basis of an already existing matrix of sensor responses, and these can be compared to human memory or association to existing taste patterns [14, 22]. Figure 11.2 presents a simplified flowchart of the electronic tongue system.

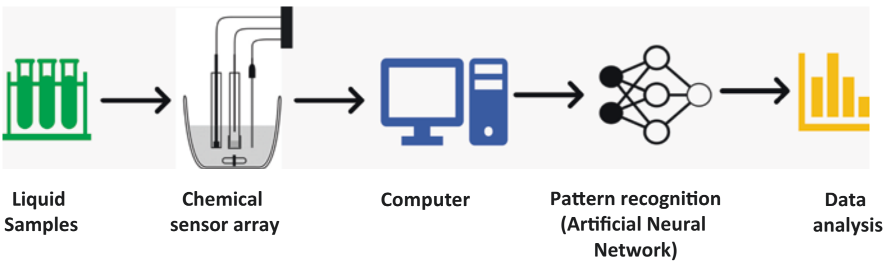

Fig. 11.2 Simplified flow chart of electronic tongue system. This system imitates what is happening when molecules with specific taste nature interact with taste buds on the human tongue. The taste buds are represented by sensors which interact with these molecules at the surface initiating changes in potential. These signals are compared with physiological action potentials which are recorded by computer (pattern recognition), which correspond to the neural network at the physiological level. The data obtained can further be evaluated using statistical methods based on already existing matrix of sensor responses

Currently, two major electronic tongue systems are commercially available: the taste sensing system SA402B (Insent Inc., Atsugi-chi, Japan) and the ASTREE e-tongue (Alpha M.O.S, Toulouse, France) [23, 24]. Both of these measures change in electronic potential while investigating liquid samples but the underlying sensor technologies are different. The taste-sensing system SA402B is equipped with lipid membrane sensors, whereas the ASTREE uses chemical field-effect transistor technology [24]. In addition, other taste-sensing systems are under development. An electronic tongue system is generally made of the following parts:

3.2 Different Sensor Arrays

In an e-tongue, the output of the nonspecific sensor arrays shows different patterns for different taste-causing chemical substances, which is statistically analyzed. Thus the e-tongue can be defined as "a multisensory system for liquid analysis based on chemical sensor arrays and a suitable pattern recognition method" [14]. Regarding the sensor arrays used in the design of e-tongues, a wide variety of chemical sensors have been employed, which include electrochemical (potentiometric, voltammetric, amperometric, impedimetric, conductimetric), optical, mass, and enzymatic sensors (biosensors) [1, 25–27]. The most applied operational principle of the e-tongue is typically voltammetry or potentiometry [28]. A potentiometric E-tongue system generally consists of the following parts:

Working Electrode: The working electrode is an inert material such as Gold, Platinum, Glassy Carbon, iridium, and rhodium [24]. The working electrode serves as a surface on which redox reactions occur. The surface area should be very less (few mm^2) to limit the current flow [24].

Reference Electrode: An Ag/AgCl reference electrode is used in measuring the working electrode potential. A reference electrode should have a constant electrochemical potential as long as no current flows through it [23, 24].

Auxiliary electrode: A stainless steel counter electrode is a conductor that completes the cell circuit. It is generally an inert conductor. The current flow into the solution via the working electrode leaves the solution via the counter electrode [23]. A relay box is used, enabling the working electrodes to be connected consecutively to form four standard three-electrode configurations [24]. The potential pulses/steps are applied by a potentiostat which is controlled by a PC. The PC is used to set and control the pulses, measure and store current responses, and operate the relay box [23, 24]. Figure 11.3 represents different components of a potentiometric E-tongue system.

Potentiometric sensors are the most widely used type in e-tongue systems, especially ion-selective electrodes (ISEs) [14]. The main disadvantages of potentiometric sensors are their temperature dependence and the adsorption of solution components that affect the membrane potential [14]. These factors can be minimized by controlling the temperature and washing the electrodes. On the other hand, the advantages of potentiometric sensors include their well-known operation

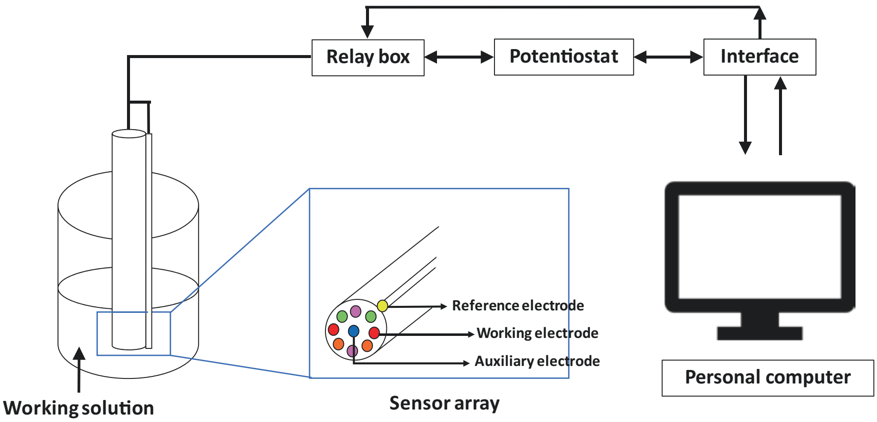

Fig. 11.3 Schematic diagram of a potentiometric type E-tongue. Sensor array is comprised of reference, auxiliary and working electrodes. These sensors measure dissolved organic compounds in liquids including taste and flavor compounds. A relay box is used to enable the working electrodes to be connected consecutively. The potential pulses/steps are applied by a potentiostat which is controlled by a personal computer. This computer is used to set and control the pulses, measure and store current responses and to operate the relay box

principle, low cost, simple set-up, easy fabrication, and the possibility of obtaining sensors selective to many various species [29].

Voltammetric sensors are also extensively used in e-tongue systems. These devices are advantageous for multicomponent measurements because of their high selectivity, high signal-to-noise ratio, low detection limits, and various modes of measurement [14]. Furthermore, the surface of the electrodes can be modified with various chemosensitive materials obtaining sensors of various sensitivity and selectivity toward a variety of species. However, their applicability is limited to redox-active substances [25].

Impedimetric e-tongues are based on the measurement of impedance either at one fixed frequency or a broader spectrum using impedance spectroscopy. They have been applied to the recognition of basic taste substances, beverages, and mineral waters, and these have been shown to have excellent sensitivity [30]. Moreover, there is no requirement of active species in the measuring system, and unlike other electrochemical methods, when they do not require a standard reference electrode (which might be troublesome in many practical applications because a reliable reference is a critical issue in miniaturized sensor arrays) [14].

In an amperometric e-tongue, an electrochemical conversion occurs (potentiostatically) at an electrode, and the resulting current due to this electrochemical reaction is measured. With the amperometric method, only partial electrolysis takes place. To be detected by amperometric e-tongue, the compound of interest has to be electroactive (at the applied potential, in the solution used, and at the prevailing pH) [1]. This is both a limitation and an advantage. This electrode can only be used to detect electroactive species, which is a major limitation. On the other hand, the selectivity of the electrode can be considered as a key advantage of amperometric e-tongue. Thus, it is possible to detect electroactive components without the interference of the non-electroactive compounds. Using an array of sensors working at different potentials, it is possible to resolve between several electroactive compounds, since at low positive/negative potential, only strong reducing/oxidizing compound may be detected. On the contrary, at large detection potentials, the total electroactive compounds are detected [1].

Optical sensors are also used in e-tongues technology. These devices offer several modes of operation, such as fluorescence, absorbance, and reflectance. Additionally, analytes are difficult to detect electrochemically (e.g., uncharged and/or non-electroactive), and it can often be studied with optical sensors. However, some drawbacks, such as sensor preparation, durability, and signal interferences, limit their applications [31]. Optical e-tongues have been mainly used in biomedical analysis and food analysis [14].

3.3 Data Processing

Apart from the sensor arrays, signal processing is an important aspect of multisensory analysis. In a multicomponent environment, the sensor array produces complex signals (patterns) that contain information about different compounds and other features. These signals should be analyzed together to extract valuable analytical information. Various methods of multivariate calibration and pattern recognition are now available and can be used for sensor array data processing. The electronic tongue may be applied in principle to two main tasks: (i) quantitative determination of the content of components and (ii) classification (recognition, identification, and discrimination). The choice of the data processing technique for a particular case depends on the task to be solved and the structure of the data (nonlinearity, correlations, etc.). A brief overview of some data processing methods, together with their main features, is presented in Table 11.1 [32].

4 Applications of Electronic Tongue in Food Safety and Quality Assessment

To ensure food quality and to comply with the safety requirements, food products need to be monitored and controlled consistently during the entire food supply chain. For this purpose, the electronic tongue system appeared to be an ideal device, as it enables fast, precise, and direct analysis [33]. Moreover, an electronic tongue can be applied for automatic online monitoring during food processing. The following sections briefly describe the most relevant applications of taste sensors, such as sample recognition/origin tracing, freshness evaluation, process monitoring,

Table 11.1 Selected methods of multivariate calibration and pattern recognition used for electronic tongue data processing

Method	Linear	Supervised	Advantage	Drawback
Principal component analysis (PCA)	Yes	No	Easy to interpret	Sensitive to the drift in the data
Partial least squares (PLS)	Yes	Yes	Statistical description of the results Small calibration data set	
Self-organizing map (SOM)	No	No	2D representation of data of any dimensionality	Works as black box
Back propagation neural network (BPNN)	No	Yes	Easily deal with nonlinear data	

authenticity assessment, quantitative analysis, and quality control. Applications of the electronic tongue in relation to different categories of foods are presented in Table 11.2.

4.1 Foodstuff Recognition and Characterization

An electronic tongue comprising 17 ion-selective electrodes can be applied to discriminate between different brands of mineral waters and apple juices [14, 16]. Since the main components of mineral water are ionic, high-selective sensors were able to easily differentiate the water samples. However, in the case of juice samples, a lower recognition accuracy was obtained due to ionic inorganic but also organic species characterizing juice taste [14]. To solve this problem, a system based on selective and partially selective sensors was developed to discriminate between different brands of orange juice, tonic, and milk with an accuracy of 90–100% [14]. In this way, the combination of two types of sensors provides a versatile device for qualitative analysis of various types of beverages.

Researchers have proposed a hybrid electronic tongue based on a combination of potentiometry, voltammetry, and conductivity measurements for the classification of six different types of fermented milk [34]. Using data from the voltammetric, potentiometric, and conductivity measurements, independently, a partial overlapping between sample classes was observed. However, it was reported that the combination from all information sources could separate all six samples [14].

4.2 Authenticity Assessment

Food authentication is one of the greatest concerns for researchers, consumers, industries, and policymakers. An authentic raw material or finished product has to comply with labeling in terms of ingredients, brand, origin as well as production

Table 11.2 Applications of the E-tongue in relation to different categories of foods

Sample	Type of study	Principle of detection	References
Milk	Detection of adulteration of samples with cow milk	Potentiometry	[54]
	Freshness monitoring	Voltammetry	[55, 56]
	Quality and storage time monitoring	Voltammetry	[57]
	Classification of milk samples	Potentiometry	[58]
	Detection of antibiotic residues	Potentiometry	[59]
	Detection of clinical mastitis	Voltammetry	[60]
Bacteria cultures used in cheese production	Fermentation process monitoring	Potentiometry	[61]
Red wines	Discrimination among 12 Spanish red wines	Voltammetry	[62]
Wines	Monitoring of wine aging	Potentiometry	[63]
Beer	Correlation with human taste panel scores	Potentiometry	[64]
	Variability monitoring of brewing process	Impedance	[65]
	Monitoring of fermentation process	Impedance	[65]
Tea	Determination of caffeine and catechins in green tea	Voltammetry	[66]
Coffee	Tastes of different kinds of coffee	Potentiometry	[4]
Fruit juice	Semi-quantitative and quantitative analysis of non-alcoholic beverages	Potentiometry	[67]
Tomato	Analysis of tomato taste	Potentiometry	[68]
Apricot	Discrimination between apricot varieties	Potentiometry	[69]
Apples	Discrimination of varieties and determination of organic acids	Potentiometry	[70]
Pear	Determination of sugar content and firmness of non-climacteric pear	Voltammetry	[71]
Olive oil	Detection of olive oil adulteration	Voltammetry	[48]
Meat	Prediction of NaCl, nitrate, and nitrite contents in minced meat	Impedance, voltammetry	[72]
Fish	Discrimination between storage times, prediction of chemical and biochemical degradation parameters	Potentiometry	[73]
	Prediction of fish degradation degree	Voltammetry	[74]
Rice	Sensory evaluation of milling	Voltammetry	[75]

technology. Information about the geographical origin is also crucial since it may affect the price [35]. E-tongues have proven their potential in the authenticity assessment of different kinds of foods due to their simplicity, efficiency, speed, and low cost of the determinations [14].

Frequently studied food products in terms of label authentication are oils, dairy products, alcoholic and non-alcoholic beverages, honey, tea, and coffee. An electronic tongue constructed with an array of 20 all-solid-state potentiometric electrodes with polymeric membranes can be used to differentiate. One of such studies demonstrated that electronic tongue can be used to classify honey samples according to the most predominant pollen type with reasonable efficiency (84% and 72% of success in calibration and cross-validation, respectively) [36]. The same tool also presented a promising behavior for monofloral honey assortment. This type of electronic tongue can also be used to detect raw goat milk adulterations with raw cow milk [37]. However, to use this electronic tongue as a routine methodology, it is needed to improve the multisensor system by testing and including more sensible sensors to milk composition variations [14].

Another important application area of electronic tongues is the authenticity assessment of vegetable oils. A potentiometric electronic tongue containing cross-sensitive lipid membranes was applied to discriminate monovarietal extra virgin olive oils according to olive cultivar and geographic origins. Recorded signals were analyzed by meta-heuristic simulated annealing algorithm together with the LDA resulting in sensitivity above 97% [38].

Studies on the fraudulent performances are increasingly carried out in different alcoholic beverages, and among them, wines are the important targets. Electronic tongues have been used for the identification or authentication of wines according to grape variety or their geographical origins, brands and for the detection of fraudulent samples derived from deliberated addition of chemicals to wine to correct or enhance its organoleptic properties [14]. In this context, a hybrid array of voltammetric sensors formed by different families of sensitive materials (phthalocyanines and conducting polypyrrole polymers) can be used to detect various chemical adulterations in wines and other beverages [14]. Another study presented a portable electronic tongue system based on disposable screen-printed electrodes capable of distinguishing between different types of Lager beer, predicting its color and alcoholic strength (accuracy of 76% and 86%, respectively) [39]. A very recent study of a novel paper-based potentiometric electronic tongue with an integrated reference electrode demonstrated that it can be served as a tool for discriminating beers from 19 brands and 12 different types [35]. Moreover, it allowed the detection of stabilizers, antioxidants, dyes, and substances added during the fermentation process [35]. In the case of wine, samples could be classified according to the grape variety. A significant advantage of the system is its low cost, adaptability, and ability to work with microliter sample volume [40].

4.3 Freshness and Food Quality Evaluation

The quality of food products is the ever-growing interest of the consumers. Electronic tongues have the potential to predict the freshness or spoilage of different foods like meat, fish, seafoods, raw materials, and other food products. In case of meat and fish products, freshness evaluation is highly important because rotten or spoiled products may negatively affect the health of consumers. Therefore, a multi-sensor system based on modified screen-printed electrodes has been tested as a possible tool for the detection of ammonia and putrescine (toxic diamine produced during decomposition of amino acids) in a powdered beef extract [35, 41]. The proposed sensor matrix showed an excellent sensitivity toward amine compounds (LOD of 1.85 mol/L for ammonia and 0.34 mol/L for putrescine) [41].

The application of electronic tongue to evaluate fish freshness has also been reported [14, 42]. Experimental results demonstrated the usefulness of electronic tongues for in situ and at site freshness evaluation, and it could be used as an alternative to other destructive, high-cost, and time-consuming methodologies [14]. In an experiment, the evolution with time on fillets of cultured sea bream (*Sparus auratus*) using a potentiometric electronic tongue containing 16 electrodes was used [42]. Fish freshness indicators, such as texture, pH, color, microbial analysis, total volatile basic nitrogen, and biogenic amines, were also determined with respect to time. Multivariate analysis of electronic tongue data allowed the assessment of the storage time of fish fillets with a rate of success of 100% [42]. On the other hand, good correlations were found between potentiometric data and fish freshness indicators with correlation coefficients higher than 0.90 [42]. In another study, two voltammetric e-tongues based on carbon paste or screen-printed electrodes modified with phthalocyanines were developed and applied to monitor fish spoilage. The screen-printing technology allowed for the preparation of miniaturized electrodes, which are promising for the fabrication of low-cost sensors with higher sensibility compared to the corresponding modified carbon paste electrodes [43].

4.4 Process Monitoring

Electronic tongues can also be successfully applied for the monitoring of changes occurring in the composition of foodstuff during its production. One of the most significant applications is the fermentation process. Continuous control of the fermentation helps to avoid unfavorable deviations, detect microbiological contamination, and ensure the feasibility of the processes [44]. In many cases, mixed cultures of microorganisms are used, which trigger themselves at specific time points of the process. In addition, due to the variations in the composition of major substance used in the process, it is difficult to find any other analytical technique that could be reliably applied to analyze fermentation samples. Electronic tongue systems are able to deal with such samples that are extremely complex, present huge variations in the background composition, and have to be studied in detail as in some cases lack of certain nutrient can stop the process or lead to unwanted by-products [44, 45]. A study showed that an electronic tongue based on potentiometric sensors can quantify organic acids (such as citric, lactic, and orotic) in the fermentation media with average prediction errors in the 5–13% range while conducting in both "normal" and "abnormal" operating conditions. Electronic tongue has thus become a promising tool for fermentation process monitoring [46].

In the dairy industry, the demands of sensors are gradually increasing as they are able to withstand extreme conditions (hot base and acid solutions), hygienic, and can be sterilized easily. Also, no reference electrode is allowed [14]. Researchers have demonstrated that specially designed voltammetric electronic tongues were inserted in the process line of a dairy industry for direct inline measurements, and they were in operation for 8 months without any malfunction and maintenance [34]. The electronic tongues were used to follow different sources of raw milk coming into the process and to monitor the cleaning process of the pasteurization unit.

An electronic tongue based on voltammetric electrodes chemically modified with different sensitive materials (polypyrrole, metallophthalocyanine derivatives, and perylene derivatives) can be used to monitor the aging of red wines and to discriminate wine samples aged in oak barrels of different characteristics [47]. The diversity of the sensing materials in the electronic tongue allowed obtaining a high cross-selectivity in the responses of the sensors forming the array. Multivariate inspection of voltammetric data as used in e-tongue showed a high capability of discrimination and classification.

4.5 Quantitative Analysis

An electronic tongue composed of a polymer membrane sensor array and data processing routines can be used as an analytical tool for quantification of saltiness (NaCl) and sourness (citric acid) in synthetic taste solutions as well as for discrimination between wines from different grapes [14]. A study showed that electronic tongues, based on 23 potentiometric cross-sensitive chemical sensors, can measure several quantitative parameters of the wines (total and volatile acidity, pH, and contents of several wine components) with precision within 5–12% [16]. In addition, the system is capable to predict human sensory scores with precision errors within the 4–27% range [14].

Apart from wine and grape juice samples, electronic tongues can be used for the determination of taste compounds in other kinds of foodstuffs. An electronic tongue comprising of voltammetric electrodes as modified by different sensitive materials was proposed to evaluate the phenolic content of extra virgin olive oils [43]. Brazilian researchers have recently shown that an artificial hand-held tongue of four sensors made from ultrathin films deposited on gold interdigitated electrodes was able to distinguish the four basic tastes [46]. Some of the samples, e.g., 5 mm NaCl and sucrose, were detected below the human threshold level, and suppression of quinine by sucrose was also observed. The high sensitivity was attributed to the ultrathin nature of the films. By using four sensors for the different tastes, an electronic fingerprint of the taste was obtained. These responses were combined into a single data point which allows predicting the taste of a particular solution [46].

4.6 Food Safety Assurance

The intentional addition of inferior quality material as well as biological and chemical contamination during the period of growth, storage, processing, transport, and distribution of the food products pose a serious risk to the consumer's health. Thus, developing quick and precise methods for the detection of contaminations in food products is of the highest importance. Electronic tongues can play a very important role to detect adulterants. One of the examples includes the examination of virgin olive oil adulteration [48]. An array of modified carbon paste electrodes was employed for the evaluation of the percentage content of edible oils (sunflower, soybean, and corn oils) in olive oil samples. Data obtained after processing of voltammetric signals using PLS (partial least squares) discriminant analysis and regression demonstrated the ability of the sensor to classify precisely the aforementioned adulterant oils with a concentration level below 10% [48].

Recently, an automated hydrodynamic bioelectronic tongue based on genetically modified acetylcholinesterase was applied for the quantification of pesticide (chlorpyriphos-oxon and malaoxon) mixtures in milk [49]. In another study, a voltammetric electronic tongue enabled quantification of formaldehyde, urea, and melamine in milk with limits of detection (10.0, 4.16, 0.95 mmol/L, respectively) below the limit of the recommended tolerable intake dose [50]. A different study described a voltammetric electrode array which showed that it was able to predict levels of the most widely used curing agents, nitrate, nitrite, and chloride in minced meat and saline solution [51].

Finally, another recent, important application of electronic tongues is the monitoring of organophosphate pesticides at nanomolar levels in food items [35]. The presence of pesticides in foods can not only cause a number of health effects but is also linked to a range of serious illnesses and diseases in humans, from respiratory problems to cancer. The potential presence of pesticides forces additional quality control in the case of vegetables and fruits as they are toxic. Before the development of electronic tongue, many analytical methods have been developed to detect these compounds such as chromatographic and spectroscopic techniques.

5 Future Directions

Being an advancing biomimetic measurement technology, electronic tongue makes the use of sensor arrays that combine both hardware and software to exhibit high performance in analyzing the product and process quality. However, the concept of biomimetics should not be exaggerated, as they cannot be as effective as the human sensation, which is strongly linked to the signals from the brain and memories about previous taste experiences [52]. Artificially designed sensor arrays give results based only on smell, and they do not follow the same mechanism as the human senses. Also, there are several difficulties associated with sensors manufacturing, such as reproducibility, drift, and the transfer of properties from one lot of sensors to another. This learning and understanding are important, as we continue to use man-made sensor arrays in biomimetics for a wide range of applications [52]. Regardless of these concerns, the future for the electronic tongue appears to be promising as it can fulfill niche analyses. Research and algorithm development activities for data analysis in an efficient manner are continuing apace in different laboratories around the world. Since the early instruments have performed well for some applications, it is believed that the newer prototypes could be advanced in the field further. Researchers are investigating the application of electronic tongues as a detection scheme in flow-based analytical systems. It is remarkable that flow-based electronic tongues are currently experimenting, which confirms them as a trend in modern analytical chemistry. There is no doubt that these systems may be used for the resolution of more complex analytical problems, increasing the number of analytes to be determined, and also the identification/classification of even more similar samples [14]. The other key areas for future development can be envisioned inline monitoring of food production process, especially alcoholic fermentations.

6 Conclusion

The unique capabilities of electronic tongue systems, such as the ability to deal with complex and changing background and diminish the impact of interferents are the reasons of their paramount importance. Electronic tongues have become a very promising and prospective field of chemical sensor science. In addition to being a multicomponent quantitative analysis instrument, different sensing techniques, possible use of unconventional fabrication methods and numerous data treatment procedures indicate that electronic tongue systems can be tailored to various application areas. The strengths of the electronic tongue include the fact that they are easy to build, cost-effective, and provide a short time of analysis [46]. Also, they have greatly reduced the exposure and risk of using human panel to test food products, permitting better analytical results to quickly define the best formulation and get the product to the market. Therefore, these devices are becoming more and more popular to monitor food safety and quality assessment of foods. Although some electronic tongues have already been offered commercially, this is still an emerging scientific direction and more research has to be carried out in order to implement them in the process production widely. Major concerns include the lack of intermediate precision studies (i.e., using different operators or instruments) and long-term studies, more validation studies, and higher number of analyzed samples being required in some cases to extract more reliable conclusions [53]. To expect new achievements in the upcoming future, extensive efforts are needed in sensing mechanism studies, in the development of new sensor compositions, and in the procedures for the application of electronic tongues to practical tasks.

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