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Editorial

Emerging Trends of Electrochemical Sensors in Food Analysis

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Food quality and safety pose an increasing threat to human health worldwide. The development of analytical methods and techniques to ensure food quality and safety is therefore of great importance. For this purpose, electrochemical sensors are emerging as suitable analytical tools as they provide a low-cost and sensitive option based on portable devices capable of rapidly detecting a range of analytes with high sensitivity and specificity. They have the potential to overcome the restrictions and limitations of traditional methods. Additionally, these sensors have special recognition capabilities for a wide range of molecules, with high stability under extreme experimental conditions. This paper reviews the progress of using electrochemical sensors applied to the food industry, namely to the field of quality and safety evaluation. Future perspectives and challenges are also discussed.

Food quality and safety are the main targets of investigation in food production. Therefore, reliable paths to detect, identify, quantify, characterize and monitor quality and safety issues occurring in food are of great interest. Many analytic methods, including chromatography methods such as gas chromatography (GC), high performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS), or immunological detection, such as enzyme-linked immunosorbent assay (ELISA) and lateral flow immunoassay, have been employed for food quality and safety monitorization. Although these traditional methods are relatively sensitive and specific, they are expensive, laborious and time-consuming and require well-trained technicians, which make them incompatible for developing countries and areas which are lacking equipped facilities and specialists. In this sense, the food industry needs practical, fast, low-cost, accurate, sensitive and in situ and online technologies for food quality and safety monitoring/evaluation [1].

Electrochemical sensors have been reported in numerous academic and industrial applications, namely at food, pharmaceutical and environmental levels, demonstrating their increasing commercialization and importance as analytical devices, not only for their long-term dependability, high sensitivity and accuracy but also for their low cost, speed and ease of downsizing [2].

During the past few decades, several nanomaterials with extraordinary characteristics, such as metals, conductive polymers, metal oxide, and metal–organic and carbon-based nanomaterial frameworks, have been included in electrochemical assays to promote analytical performance. This modification allows for increasing the loading capacity using recognition molecules, such as enzymes, antibodies and aptamers, as well as bioinspired receptors, which can capture targets specifically and effectively, thereby increasing the specificity of the electrochemical sensors. This is closely related to the aim of providing strong electrocatalytic activity for certain electrochemical processes. In addition, by altering the surface shape and structure, it is possible to increase both the electrical conductivity and surface area, which should enhance the sensitivity of these tests. Electrochemical sensors have gained popularity recently owing to new applications such as single-molecule sensing, in vivo analysis, wearables and point-of-care diagnostics [3].

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This type of sensors can be classified into several categories including amperometric, potentiometric, voltammetric, impedimetric, photoelectrochemical and electrogenerated chemiluminescence [2].

The data processing of the multivariate output data generated by the arrays represents another essential part of the electrochemical devices concept. The statistical techniques used are based on commercial or specially designed software using pattern recognition routines such as principal component analysis (PCA), cluster analysis (CA), partial least squares (PLS), linear discriminant analysis (LDA) and artificial neural network (ANN) [4].

A good example of an electrochemical sensor device widely applied for food analysis is the electronic tongue (E-tongue). Its working principle has been inspired by the human tongue recognition of taste sensations. In the human tongue, the perception of basic tastes is generated by 10,000 taste buds (each one with 50–100 taste cells) located in the tongue, whereby the information is then processed by the human brain. Similarly, E-tongues also establish the overall chemical fingerprint of a specific liquid matrix through an array of nonspecific sensors. Then, the generated electrochemical profiles are treated using chemometric tools and artificial intelligence to fulfill a similar goal, that is, to qualitatively or quantitatively evaluate the physicochemical or sensory profile of the sample under analysis to be able to classify the samples according (or not) to a prespecified attribute or quality [5,6].

Regarding the application, electrochemical sensor devices have emerged as analytical tools in the food industry. Food and beverage industries pay enormous attention to quality monitoring, sensory evaluation and freshness assessment of their products. These basic requirements have encouraged the development of novel analytical techniques aiming to minimize or complement the usual conventional analytical methods that in most cases are expensive, require skilled technicians and require long analysis times.

Recently, Nehra et al. [7] published a review concerning the detection of milk allergens using electrochemical biosensors. This review paper focused on research advances in biosensors, specifically immunosensors and aptasensors, to detect milk allergens.

Moreover, Tian et al. [8] reported an overview of the different and widely used approaches in biosensing for shellfish toxin detection, emphasizing the importance of electrochemical biosensors and of impedimetric ones.

Additionally, antibiotics are a group of pharmaceutical drugs widely used in human and veterinary medicine for treating many different infectious diseases. Large amounts of antibiotics are used for animals, which produce residues in food products, such as meat, chicken, egg, milk, honey and fish. Residues of these drugs can induce several toxic effects in humans. To minimize the adverse effects of antibiotics, the European Union has banned some specific antimicrobials, while for those not banned, maximum residue limits (MRLs) have been established to ensure consumer safety from the ingestion of antibiotic residue in animal-derived foods. In this sense, the literature has reported the biosensing approaches for antibiotic detection.

Majdinasab et al. [9] presented and highlighted the achievements in developing biosensors in the above-mentioned application field, evidencing the different types of involved nanomaterials and the biorecognition elements.

Recently, Sun et al. [10] revised the current antibiotic detection technologies, including chromatography, mass spectrometry, capillary electrophoresis, optical detection and electrochemistry, evidencing the advantages and drawbacks.

Arrieta et al. [11] reported the successful application of E-tongues for identifying coffee samples adulterated with roasted corn and roasted soybean. In addition, Wang and Sun applied the E-tongue to an early detection tool for assessing apple juice spoilage due to the presence of *Zygosaccharomyces rouxii* [12].

In fact, E-tongues have been applied to olive oil analysis, namely for assessing oils' geographical origin, identifying the olive cultivar, establishing chemical and sensory profiles, characterizing olive oils with different degrees of bitterness, monitoring the quality and oxidative stability of olive oils during storage, as well as evaluating that of their shelf life, detecting adulterations with other vegetable oils or with low-chemical or low-sensory-quality olive oils and evaluating olive oils obtained from olives produced by centenarian trees [13–23]. Recently, Marx and coauthors [24] offered a brief review about the application of electrochemical sensor tools for assessing bioactive compounds in olive oils, showing the versatility and potential of this type of device. Additionally, this electrochemical device was shown to be a practical and powerful classification taste tool for assessing the commercial grade of table olives considering both positive and negative organoleptic attributes, with a satisfactory and similar quantitative performance as that achieved by a trained sensory panel [25–27]. Moreover, these tools were capable of satisfactorily monitoring the changes occurring during the debittering of traditional stoned green table olives [28].

Arduini et al. [29] evaluated the capability of biosensors to detect pesticides in olive oil samples. The authors demonstrated that the sensitive butyrylcholinesterase/black carbo-based screen-printed electrode biosensor showed optimum reproducibility, as well as good analytical performances with a low detection limit (6 ppb) of organophosphorus pesticide in olive oil extract. The results obtained suggest that the biosensor proposed may be considered as an adequate analytical instrument for analyzing contaminants in olive oil.

Food packaging is an important factor to preserve and maintain the quality of food products. The use of intelligent packaging constitutes an innovative path to provide more accurate information not only for the suppliers but most importantly for the consumers. Intelligent packaging with biosensors, which is a special application of sensors, also deserves special attention. There is a significant difference between chemical sensors and biosensors in the recognition layer. Chemical sensors consist of a layer designed to recognize the chemical compound. In contrast, biosensors are composed of receptors of biological materials, i.e., antigens, enzymes, nucleic acids or hormones [30,31]. Biosensors work on the principle of monitoring and detecting biological reactions in controlled products. Additionally, such a biosensor becomes an integral part of the packaging or is located directly within it [32]. Bio-based sensors for smart food packaging have been applied to provide information about the degree of freshness of a product and have been mostly employed in perishable products such as milk, meat, fish and seafood, among others.

For example, Magnaghi et al. [33] observed that the miniaturized BCP-EVOH@ sensor, made of bromocresol purple (BCP) and covalently bound to the ethylene-vinyl alcohol (EVOH) copolymer, meets the goal of milk freshness monitoring during chilled storage, allowing both naked-eye evaluation and chemometric-assisted spoilage modeling.

However, despite the innovation and development of new intelligent and smart packaging materials that are bio-based, there are still some limitations and, according to the literature and market research, no suitable solutions are currently commercially available [34].

Introducing new methods for food analysis is one of the most important issues in food quality and safety control. Electrochemical sensor devices can be viewed as emerging and promising analytical devices that, depending on the implemented electrochemical technique, can be very useful as quality and monitoring control tools for food industry applications among other fields, being fast, clean, green and cost-effective analytical devices. However, the mass application of electrochemical sensors in the food industry still seems to be a challenge. In this sense, future research could concentrate on constructing miniature and portable arrays which combine, within the same device, sensors for the analysis of gas, liquid and color even with enzymatic biosensors capable of selectively, precisely and rapidly monitoring/determining the quality and safety of food products at the industrial level.

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