History and Basic Principle of E-Nose

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Fermented foods and beverages have become a part of daily diets in several societies around the world. Emitted volatile organic compounds play an important role in the determination of the chemical composition and other information of fermented foods and beverages. Electronic nose (E-nose) technologies enable non-destructive measurement and fast analysis, have low operating costs and simplicity, and have been employed for this purpose.

E-nose gas sensor Electronic nose electronic sensing odor assessment

chemosensor Machine olfaction sense of smell Artificial Intelligence

1. Introduction

Due to uncertainties and unpredictable crisis situations (e.g., war conflicts) and global pandemics, the demand for fermented food and beverages has been significantly increasing because they are easy to cook and have a long shelf life [1]. In the production of fermented foods and beverages, different types of microorganisms, such as bacteria, yeast and mold, have been used to modify the chemical composition, resulting in changes in taste, smell, color and nutrients. For example, fermentation with probiotic microorganisms such as a lactic acid bacterium in products such as yogurt, kefir and kimchi can increase the nutritional value, for example, by reducing cholesterol and promoting healthy digestive function [2]. In countries, the fermentation technique has been developed specifically from local wisdom to large-scale manufacturing industries by selecting pure microbial strains, resulting in unique fermented foods and beverage products, such as pla ra (fermented fish) in Thailand, Chinese kombucha, Indonesian tempeh, natto and miso in Japan, Korean kimchi, etc. In the fermentation process, microorganisms can produce a variety of enzymes to modify food precursors. For example, the fermentation of natto employs bacteria of the genus *Bacillus* to create a fibrous texture that is sticky and stretchy [3]. The fermentation of coconut water (nata de coco) is produced via the bacterium *Acetobacter xylinum* [4]. Fermented tofu employs *Monascus purpureus* [5]. Different microorganisms make products with distinctive flavor compounds, nutrients and shelf lives.

To assess the quality of fermented food and beverages, such as the physical quality, nutrition value, microbiological quality, safety and sensory quality, there have been several types of equipment and techniques developed, ranging from spectroscopies to sensory evaluation techniques [6][7][8][9][10]. Equipment and methods enabling non-destructive measurement, rapid analysis and on-site testing with low operating costs and simplicity have received great interest in recent years. One of the effective tools for qualitative food and beverage identification meeting these criteria is an electronic nose (E-nose). There is a global trend in the development of E-nose systems instead of standard equipment such as GC, GC/MS, SPME/GC-TOFMS, GC-IMS, etc., in the qualitative analysis of food and beverages [11][12][13][14][15][16][17][18][19][20]. Although there are a set of review articles on the E-nose in food and beverage applications, comprehensive reviews focusing on fermented food and beverages based on E-nose technology are still limited.

2. History and Basic Principle of E-Nose

One of the first reports on the E-nose was in 1982, originated by Dodd, G. H. and Persaud, K. from the University of Warwick, England [21]. They employed three Figaro semiconducting gas sensors as transducers. The results showed fine discriminations between odors according to the mammalian olfactory system. This pioneering work has inspired several research groups to develop E-nose systems for various applications [22][23]. The concept of the E-nose is based on mimicking the human olfactory system, as shown in **Figure 1**. The mechanisms, odor recognition and limitations of human olfactory perception at a molecular level were first investigated by Buck and Axel from Columbia University, USA, in 1991 [24]. Their discovery helped to establish new ways/ideas to develop an E-nose system instead of using complex human olfactory perception for multifunctional purposes. The human olfactory system can be considered to consist of three main parts: (I) the odor-receiving part, consisting of olfactory receptor glands and scent delivery systems [25], (II) the nervous system for the transmission of signals between the brain and the rest of the body and (III) a decision system that is able to recognize, identify and act on the sense of smell experienced via the brain. The mechanism of smell perception is very complex. On the basis of psychophysical testing, humans are able to discriminate > 1 trillion olfactory stimuli [26]. However, the emotions and age of humans have a significant effect on odor recognition and classification [27][28][29]. Moreover, toxic agents in the sample and testing time are crucial obstacles in the ability to identify smells via the human olfactory system. The E-nose has thus become one of the powerful tools as an alternative to human evaluation of scent in samples.

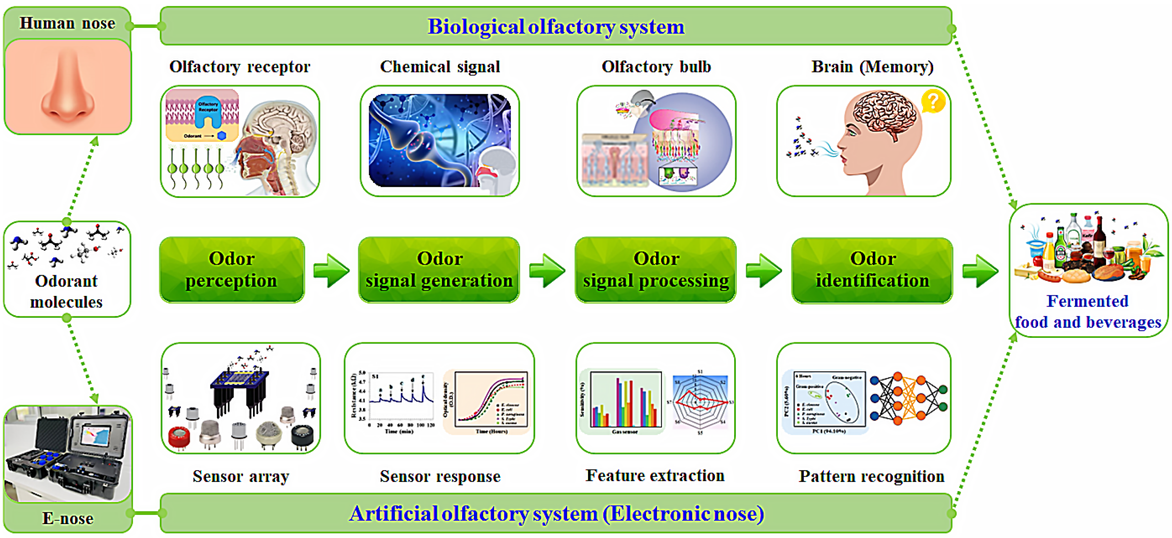

Figure 1. Schematic diagram of E-nose device versus biological olfactory system.

A comparison between an E-nose system and the biological olfactory system is displayed in **Figure 1**. In the E-nose system, the olfactory receptor section consists of the odor delivery unit (including the pipes, pumps and valves), which creates a path for aroma delivery into the sensor chamber. Numerous gas sensors, a so-called sensor array, are the heart and most important component of the olfactory receptor. Various sensing materials, such as conducting polymers [30][31], carbon-based nanomaterials [32][33][34], metal oxides [35][36][37][38] and nanocomposites [39][40], have been used to adsorb odor molecules based on both physisorption and chemisorption. When the odor molecules adsorb on the sensing material surface, they lead to charge transfers, volume expansion, ion exchange or interaction with ion species that can cause changes in the electrical conductivity/resistivity of the sensing materials. The electrical signals generated by various sensors are converted from analog to digital via an A/D converter and modified via signal processing, such as noise reduction or signal amplification. The data are stored on a local computer/online platform for further analysis. Due to the multivariate data obtained from the gas sensor array of the E-nose system, data analysis is usually performed via supervised/unsupervised machine learning algorithms with statistical methods such as principal component analysis (PCA) [41][42][43], hierarchical cluster analysis (CA) [44][45], analysis of variance (ANOVA) [46], linear discriminant analysis (LDA) [47], partial least squares discriminant analysis (PLS-DA) [48], simple visualization techniques [49], multivariate data analysis [50], artificial neural networks (ANNs) [51][52][53], artificial intelligence (AI) [54] and F-test [55]. A photograph and schematic diagram of a prototype portable E-nose system are displayed in **Figure 2**.

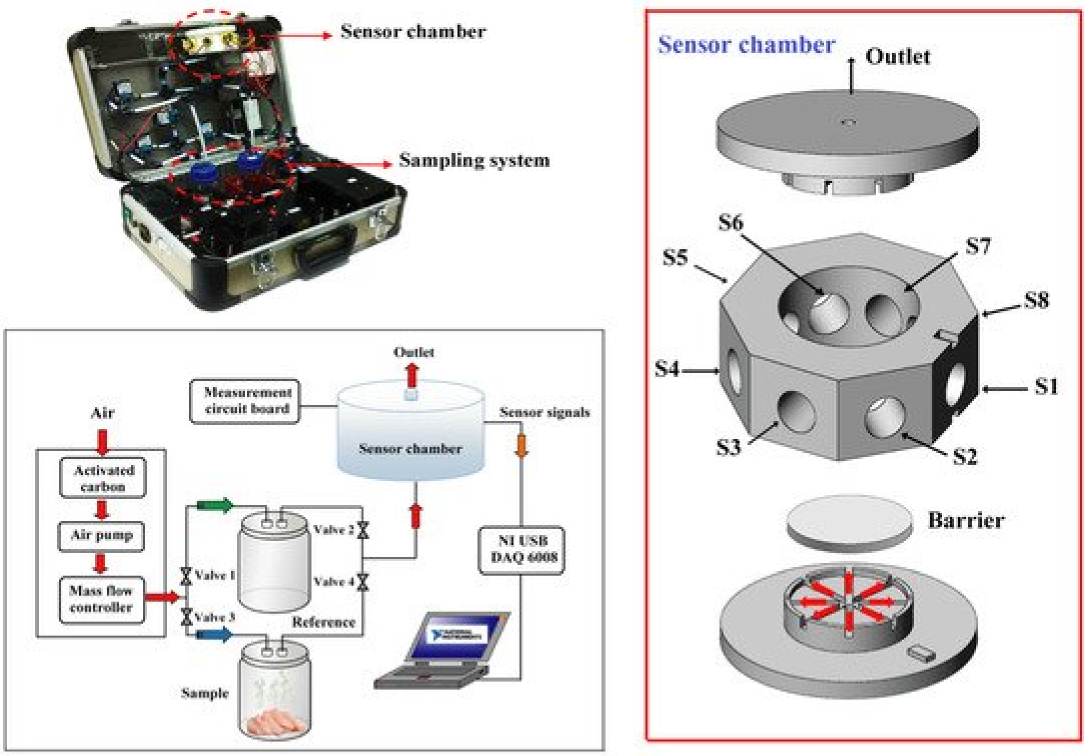

Figure 2. Photograph and schematic diagram of a prototype portable E-nose system [16].

Nowadays, E-nose systems based on a diversity of gas sensor arrays are applied in all major sectors, such as agriculture and forestry [56][57][58], industrial processes [59], environmental toxin/pollutant analysis [60][61][62], space stations [63][64], medical/healthcare [65][66][67][68], authentication of a person [69], medicine/pharmaceuticals [70], forensic science [71], military [72], toxicology/security [73][74] and the food and beverage industry [75][76][77]. Another emerging direction in the field could be to develop mobile and affordably priced devices for people who suffer from anosmia (loss of smell) [78][79]. With a focus on applications in the food and beverage industry, E-nose systems have been used for both direct/indirect identification via odor analysis for multiple purposes, such as product quality inspection [80], batch-to-batch uniformity studies [81], contamination detection [82], spoilage detection [83][84][85], adulteration detection [13][86], the detection of pathogenic bacteria [87][88], the study of storage conditions/shelf life [89][90][91][92] and the creation of specific sensory profiles [93][94]. In terms of food business competition, they have been used to analyze aromas and compare them with competitor products [95][96], evaluate the impact of changes in the production process and components that affect organoleptic characteristics [97][98] and compare different food formulations [76][99]. Moreover, E-nose systems have showed high performance in identifying the quality of many products, including wine [100], beer [101], coffee [102], carbonated drinks [103], dairy products [104][105], pork [106], beef [107][108], chicken [109], fish [110][111][112] and shrimp [113][114]. However, the sensors in E-nose systems may have a drift effect. Due to the aging of the sensors, measurements performed at different time intervals have a slight bias [115][116][117]. From the past to the present, research is still ongoing for the development of E-noses with high precision and accuracy, on online platforms, and for quantitative identification.

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