Electronic nose and electronic mucosa as innovative instruments for real-time monitoring of food dryers

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A crucial aspect of drying process is monitoring of product moisture content, nutritional value, and sensorial characteristics. This viewpoint paper considers the challenges and the opportunities in application of electronic nose and electronic mucosa as innovative instruments in drying technology in order to improve the final food quality. Electronic nose is reliable and easy to use tool in actual drying conditions. Nonetheless, the electronic mucosa, imitates nasal chromatograph effect, can provide more useful information leading to higher level of recognition than the existing electronic nose systems. Perspectives and potential employment of such tools are discussed as well.

Background
Drying is a process widely used by the food industries to hinder the growth of microorganisms, to assure the expected shelf-life of product (Aghbashlo, Kianmehr, & Arbabhosseini, 2008; Aghbashlo, Mobli, Rafiee, & Madadlou, 2013). Unfortunately, this process might occasionally lead to low quality dried foods with unpleasant sensorial properties worth mentioning due to unwanted physiochemical changes caused by inappropriate drying conditions. Furthermore, the importance of food organoleptic characteristics as first quality indicator for consumers encourage the food technologists to highlight the better preserving and improving the foodstuffs original composition, nutritional value, and functional properties during drying process. The aroma volatilization and off-odors production are the major reasons for the food deterioration during drying process, and, these reactions might alter the sensorial quality, nutritional value, and functional properties, influencing negatively on the consumer preference. Thus, the original aroma of dried product should be sufficiently kept to maintain its functionality and marketability.

Although the sensorial properties of dried products such as aroma is the key element for real-time process monitoring and consequently dryers controlling and monitoring, real-time, fast, reliable, accurate, and cost-effective aroma profiling techniques are lacking. Conventionally, aroma measurement of foodstuffs underlying different unit operations was tremendously challenging and was generally confined to off-line, time-consuming, and less efficient laboratory testing approaches. These techniques were usually based on randomly collected samples, which limited their use for real-time monitoring and accurate in-process closed-loop control. On the other hand, drying process is relatively complex, dynamic, non-linear, uncertain, and unforeseeable operation because of concurrent heat and mass transfer, fast moisture evaporation, case-hardening, and intensive chemical and biochemical reactions (Aghbashlo, Mobli, Rafiee, & Madadlou, 2012). This complexity becomes even more in the case of food drying pronounced due to product heterogeneity, anisotropicity, and non-uniformity (Nazghelichi, Aghbashlo, Kianmehr, & Omid, 2011). Hence, empirical models based on off-line measurement techniques cannot be precisely used for real-time controlling of drying process. As well, more food industries move to continuous processes, in-process monitoring that provides real-time organoleptic characteristics and feedback control that becomes even more necessary to produce
high-nutritive and cost-effective dried foods. Moreover, tight food process control is gained by reliable and precise controlling and monitoring of the process factors influencing on the food sensorial properties. However, in drying process, these factors are prone to natural inevitable changes, causing variability and difficult to foresee the sensorial attributes of final product. It is also worth mentioning the quality of foodstuffs should be examined during whole process and not only at the end-point. Thus, food unit operations should be exactly monitored and controlled in whole processing duration by use of innovative instruments to guarantee the quality of end products. These are why developing an automatic real-time aroma tracking unit in food dryers is strictly substantial to gain rigorous product sensorial attributes and reach a better understanding of the process for careful optimization of the standard operating approaches.

On the other hand, according to Quality by Design (QbD) philosophy (Drennen, 2007), quality cannot be assessed on a product but must be made and maintained into products from the beginning of a process. According to Food QbD framework, sources of variability in the drying process should be identified and hindered for improving the quality and uniformity of dried products. This can be feasible by application of real-time monitoring devices and techniques with feedback control through in-process measurements (Fig. 1A). In the most of foodstuffs drying processes, variability origins affecting on final product quality and homogeneity can be specified, monitored, and even controlled, according to Fig. 1B. Firstly, it is required to find out the relation between drying process parameters and product quality characteristics and then the origins of process variability must be monitored in timely procedure by process analyzers for precise and efficient process control (Fig. 1A). Therefore, newly designed “smart” food dryers based on QbD framework might be more reliable and cost-effective than the common ones.

Evidently, real-time measurement plays a key role in QbD scheme and according to Food and Drug Administration (FDA, 2004), real-time process measurements can be classified into three categories such as at-line, on-line, and in-line analyzers, as illustrated in Fig. 2. In brief, at-line analyzers characterize the favorable properties by withdrawing the product from process, isolating from ambient and analyzing it in close affinity to the process stream. On-line analyzers specify the desired attributes by diverting the sample from the process and returning to the process stream in most cases. In-line analyzers (invasive or non-invasive) are rapid measuring tools or probes to consider the desired characteristics without sample withdrawing by direct placing of them into a process stream. Generally, implementation of real-time measurement units to drying equipments should eventually result in control of the process with the least dried product testing and in-depth process understanding assure the end product quality.

As mentioned earlier, a more useful way to monitor and control the drying process consists of the real-time foodstuffs quality evaluation to get an actual insight about the variables concerning both process and product. Hence, drying services should be implemented with in-process automatic drying parameter manipulations to reduce the undesirable changes in the product properties and process progress. In recent years, electronic nose have been increasingly considered as an option for real-time measurements of sensorial attributes of processed foods, as this instrument provides reliable, non-invasive, and non-destructive measurements without sample withdrawing. It can be also employed in a non-intrusive mode to build up qualitative and quantitative strategies for the in-process monitoring and controlling of a food drying process. However, the advanced version of electronic nose namely electronic mucosa presents numerous advantages over electronic nose due to its additional functionality originating from its biological character. Stability, precision, reliability, rapid response, and robustness of controller are the main specifications of any industrial dryer control system (Jumah & Mujumdar, & Raghavan, 2006), which can be obtained by both instruments. Instrumentation of food dryers with advanced control tools reduces batch failure, improves reliability of process, minimizes labor cost, optimizes energy efficiency, increases predictability of quality, and augments the finished product quality and uniformity.

**Electronic nose and electronic mucosa and their potential applications in drying technology**

In most cases, food aroma contains complex mixtures of many volatile organic compounds (VOC) with various sensorial and chemical attributes. Any change in the relative concentration amounts of these compounds can often specify the odor of the product. Nonetheless, not all the volatile compounds play an identical role in sample aroma (Peris & Escuder-Gilabert, 2009; Shafiee, Minaei, Moghadam, Ghasemi-Varnamkhasti, & Barzargar, 2013). The influence of each compound is a function of its concentration and its sensorial threshold (the minimum concentration perceivable by the human nose). The ratio between these two items is known as the odor activity value (OAV). When the OAV of a compound is more than 1, it will affect on food aroma (Mistry, Reineccius, & Olson, 1997).

The change of food aroma during drying process is of great concern to the food technologists who have been spent much funds in the monitoring and automating of their plants for the foodstuffs drying. Nevertheless, variables which are generally considered at drying facilities (moisture and temperature of the inlet and outlet air, temperature and moisture content of products), do not present vision needed to specify the loss of sensorial attributes such as aroma during processing. Undesired aroma loss, change, distortion, or even destruction often occur and result in inappropriate quality of final products. How to attain the
desirable aroma and prevent unacceptable aroma is an essential work for food engineers. Therefore, it could be particularly beneficial to implement a real-time monitoring and controlling system in drying process for measurement of the lost aroma in order to achieve a homogeneous and high quality product. The aroma is caused by both enzymatic and non-enzymatic reactions as well as degradations of macromolecules in the tissues of the food during the drying process. Moreover, secondary metabolism of microorganisms is included in the creation of volatile aroma components. Therefore, awareness on the odorant compounds at processing stage is very crucial to successfully control the quality of the food product.

To date, most research attempts on the aroma components of foods have been done with complicated and luxurious tools such as gas chromatography (GC) and spectroscopy methods. The big drawback of such techniques is that they cannot measure and quantify the components in real-time and continuous mode. In spite of providing acceptable results by such techniques, but analysis time is too long and usually require expert analysts and technicians and therefore cannot be employed regularly. On the other hand, because of dynamic and complex nature of drying process, all of these instruments are inappropriate for industrial applications due to extremely operator-dependency and poor repeatability.

In recent decade, the interests in employment of the most efficient methods to monitor the food quality in drying technology have been emphasized (Mujumdar, 2007). Such interests are concerning innovative technological advances, the increasing interest in the enhancement of the quality of products, approve of more rules and standards for food, and the establishment of R&D laboratories in the industry (Ghasemi-Varnamkhasti, 2011; Shirvani, Ghanbarian, & Ghasemi-Varnamkhasti, 2014). All these circumstances have been led to make the industry more quality conscious and so, it also results in the steady advance of quality control in drying technology.

The electronic nose is an electronic system which tries to emulate the structure of the biological nose (Fig. 3). The first stage for both biological and electronic noses is the interaction among volatile compounds containing complex mixture with the suitable receptors meaning a sensor array in electronic nose, and olfactory receptors in the
One odorant is recognized by multiple odorant receptors and one odorant receptor is sensitive to multiple odorants. The next stage is the saving of the signals produced by the receptors in the brain or in a pattern recognition engine (learning stage) and later the recognition of one of the odor saved (classification stage).

The output of the electronic nose is specified by the user and can be the characterizing of an odorant, defect or attributes of the sample, concentration estimation for a certain odorant, or the specifications of the odor as it might be perceived by a human, etc. In electronic nose, each sensor in the array has overlapping sensitivities as shown in Fig. 4. For instance, odorant No.1 may generate a low response in one sensor and higher responses in others, while odorant No.2 might generate high readings for sensors instead of the one that “took” to odorant No.1. What should be taken into account is that the pattern of response across the sensors is unique for diverse odorants. This distinguish ability enables the system to characterize an unknown odor from the pattern of sensor responses before learnt. The sensors in the array have distinctive response profiles to the spectrum of odorants under study. The pattern of responses related to sensor array is addressed as a fingerprint to recognize the odor.

Electronic nose is able to detect food aroma as rapid as in seconds, which makes real-time monitoring of food aroma possible during drying for the first time. However, in comparison to the off-line measurements, in-process measurement of organoleptic characteristics is a concern in a food drying process. Electronic nose technology employs an array of semi-selective gas sensors for identification of the volatile compounds present in the headspace of a food sample (Apetrei et al., 2010; Ghasemi-Varnamkhasti, Mohtasebi, & Siadat, 2010; Ghasemi-Varnamkhasti, Mohtasebi, Siadat, et al., 2011; Lozano, Arroyo, Santos, Cabellos, & Horrillo, 2008; Lozano, Santos, & Horrillo, 2008). Advantages of electronic nose as innovative instrument consist of the fairly small amount of sample preparation that is involved and the speed of analysis compared with traditional tools like GC. Another merit of such instrument is that it is portable and can be used for any drying systems without implementation issues.

However, a few reports have been documented in the literature on application of the electronic nose for aroma measurement in food drying process. These research efforts proved the use of electronic nose coupled with chemometric techniques as a reliable instrument to aroma monitoring of drying process. Future works goes to be focused on using the electronic nose for monitoring of various food drying process and consequent automating of drying plants employing advanced intelligent controlling approaches. Until now, use of the electronic noses have kept limited just for off-line measurement (Infante, Rubio, Contador, & Moreno, 2010; Laurienzo et al., 2013; Lopez de Lerma, Bellincontro, Mencarelli, Moreno, & Peinado, 2012; Otero et al., 2003; Yang et al., 2009). It is worth mentioning the manually gathered samples for off-line measurement at the end of drying process are prone to changes in physical circumstances like humidity and temperature, which will result in non-accurate aroma analysis.

More recently, few studies have been highlighted in the bibliography on zNose for on-line monitoring of food in drying process (Dev, Geetha, Orsat, Garépy, &
Raghavan, 2011; Li, Raghavan, & Wang, 2010a; Li, Raghavan, & Wang, 2010b; Raghavan, Li, Wang, & Gariépy, 2010) and succeeding controlling based on volatile signals (Li, Raghavan, Wang, & Gariépy, 2009). So far, there exists no report on application of electronic nose for real-time monitoring of food dryers. However, real-time electronic nose has an immense potential to application in drying technology for in-process monitoring and controlling of food aroma apart from off-line electronic nose and chemical methods. For instance, a schematic diagram of microwave drying system together with zNose for aroma monitoring and controlling is depicted in Fig. 5 (Li et al., 2009). It can be stated that the illustrated diagram can be successfully applied to the most of drying equipments with minor changes. The components of the developed systems were a volatiles detection unit, which in turn included a zNose™, a two-position pneumatic valve, an air flow installation, a moisture condenser, and a flow meter.

Nowadays, electronic nose generally faces with challenging drawbacks that confine their application for real-time monitoring during drying process. Their sensitivity and detection ability is greatly influenced by usual drift caused by temperature, humidity and background noise, sensor variations, and sensor poisoning. Nevertheless, this innovative instrument uses several sensors which are not very selective for special types of compounds thus hindering any real recognition of any compound in the headspace of food sample (Reid, O’Donnell, & Downey, 2006; Rock, Barsan, & Weimar, 2008). These challenges, in addition to often wanting to measure very low concentrations (below ppm) of the odor (Ryan et al., 2004; Young, Butner, Linnell, & Ramesham, 2003), make the employment of an electronic nose more complicated even with advanced auto samplers and providing clean air. In close future when the main issues of the electronic nose have been rectified, more real-time electronic noses will be designed and implemented in drying equipments. For such applications, however, technical problems, as stated above, have to be solved for real-time monitoring and controlling. Currently, many researchers are working to overcome the problems limiting the capability of the electronic nose (Bruins, Gerritsen, van de Sande, van Belkum, & Bos, 2013; Kaur et al., 2012; Wali, 2012; Wang, Tang, Chiu, Yang, & Kuo, 2011; Zhang, Tian, Peng, & Yin, 2014). The readers are referred to the review paper complied by Gutiérrez and Horrillo (2014) in which the problems included on the application of electronic nose for real-time cases and the solutions are discussed. However, some instances of such problems are mentioned here:

1) Long sensors response time: to overcome this problem, another type of sensors could be considered, i.e. acoustic wave sensors which show a faster response or even nanowires based gas sensors are faster, less time-consuming than typical thick or thin film gas sensors. Employment of such sensor types for real-time application of electronic nose is found in the literature (Shih, Lin, Lee, Chien, & Drake, 2012).

Moreover, it should be mentioned that the food dryers are generally available in batch and continuous forms.
Batch drying method is performed through loading the drying chamber with material to be dried, developing the flow of drying media until adequately drying of material, and then evacuating the dried product from the drying unit. On the contrary, in continuous drying approach, the moist material as continuous flow is loaded to the dryer and the dried material is also evacuated continuously. In the case of batch drying mode, the drying duration is enough higher compared with the monitoring time-frame of the electronic nose system. It is worth mentioning that the drying duration of food is a function of many items such as material properties and drying conditions, typically ranging from half of hour to several hours for most of moist foodstuffs. On the other hand, continuous drying systems almost work at a quasi steady-state condition, without regard to the short-term transient startup or shutdown time, and approximately remain at a stable circumstance for a long time with the insignificant variations, until the moment of abrupt changes in the drying medium and material conditions. These dryers then quickly respond to a new drying condition and rapidly reach to the quasi steady-state circumstance again. The quasi steady-state operating time of these dryers is very longer than the monitoring time-frame of electronic nose sensors. Therefore, the monitoring time window of electronic nose cannot be a very challenging and problematic subject to hamper their successful application in food drying industry. Nonetheless, it is notable that the minimizing monitoring time window can result in more precise and extensive application of electronic nose in drying technology.

2) High amount of training data (and hence long time and high costs of training): currently many techniques are used to rectify this issue and chemometrics approaches have shown promising trend. Principal Component Analysis (PCA) before training reduces the redundancy and dimensionality of data, a remote training in servers connecting the measurement computer with labview database tool kit. Moreover, optimization techniques could be applied to select the temperatures of operation and the composition of the array in order to obtain less overlapping in the selectivities of the sensors. Poor selectivity is one of the weakest parameters of metal oxide semiconductor (MOS) gas sensor as well as of most other types of sensors (Kolmakov, 2008) in such a way to date, no a semiconductor with completely gas-specific response has been fabricated. However, numerous approaches and techniques have been developed to enhance the sensor selectivity (Chen, Shen, & Zhou, 2008; Sysoev, Kiselev, Trouillet, & Bruns, 2013; Zampolli et al., 2005).

3) Lack of reliability in the long term (need of continuous recalibrations): To deal with this problem, it can be stated that there are a lot of drift compensation techniques that could be applied, even techniques for replacing sensors. Modeling sensors drift could also be used for compensating its effect. Advanced approaches like on-line calibration have been also reported in the literature (De Vito, Massera, Piga, Martinotto, & Di Francia, 2008; Geng, Yang, & Wu, 2011; Santonico et al., 2012; Zhang et al., 2011). In recent years, the techniques for reducing the time and cost of recalibration has been explored. For instance, attenuation of the sensor failure (Fonollosa, Vergara, & Huerta, 2012; Fonollosa, Vergara, & Huerta, 2013; Pardo et al., 2000), sensor poisoning (Padilla et al., 2007; Reimann, Dausend, & Schutze, 2008), and sensor drift (Carlo et al., 2011; Padilla et al., 2010; Vergara et al., 2012; Ziyatdinov et al., 2010) has been aimed to extend the time between recalibrations. More recently active control sampling has been reported in order to minimize the number of experiments for recalibration (Rodriguez-Lujan, Fonollosa, Vergara, Homer, & Huerta, 2014).

A novel kind of electronic nose which tries to mimic nasal chromatograph effect with more useful information content in such a way higher level of recognition compared

![Fig. 5. Schematic diagram of the microwave drying system along with zNose™ for aroma monitoring and controlling (with kind permission from Li et al., 2009).](image-url)
with the existing electronic nose systems could be developed (Che Harun, Covington, & Gardner, 2009; Che Harun, Covington, & Gardner, 2012; Liu et al., 2009; Liu et al., 2010; Taylor, Che Harun, Covington, & Gardner, 2009). A typical electronic mucosa as innovative instrument is shown in Fig. 6, in which three large arrays of sensors with a two retentive columns have been combined (Che Harun, Taylor, Covington & Gardner, 2009). In this instrument, all sensor arrays provide spatial information (similar to common electronic nose, but with numerous sensors), but the second and third arrays give temporal another profiles different from each other and the first array.

As compared, the biological system employs many sensors with a various number of binding proteins, coupled with a nasal chromatograph effect comparable to a GC column. This further functionality enables the biological system to considerably act better than the present electronic nose instruments (Beccherelli, Zampetti, Pantalei, Bernabei, & Persaud, 2010). The biological system has the advantages such as higher selectivity, sensitivity, and faster response than present electronic nose system based on chemical sensor array (Dong et al., 2013). In electronic mucosa, when an odor signal passes through down a microchannel, an absorbent coating provides a delay akin to the work of the mucous layer in the nasal cavity. This absorbent material selectively does a delay in the odor signal, consequently, the generation of an odor/coating certain time delay. It is worth noting that the partitioning impact is to some extent like a traditional gas (Gardner, Tan, Covington, & Pearce, 2007).

To date, no application of electronic mucosa in drying technology has been reported in the literature, so this instrument could be very interesting to food technologists as a promising trend in real-time monitoring of food drying in order to enhance the guarantee and quality control of food products. The recent developments and achievements in the field of sensory assessment and instrumental analysis as well as the interface between humans (sensory science) and machines (instrumental analysis) show a bright future to use the electronic mucosa in food dryers.

Conclusion and perspective
Aroma is one of the most important quality indicators of food products. This attribute, to a great extent, specifies consumers’ preference and acceptance. However, in most food processing operations, aroma can be lost, altered, distorted, or even destroyed. Retaining desired aromas and limiting unpleasant aroma generation is a critical task and important goal in food dryers. To fulfill this goal, food aroma should be properly and rapidly monitored and controlled during food processing in real-time mode. In other words, a normal processing condition of foodstuffs would contain in-line in-process organoleptic attributes measurement and feedback control which can decrease human error, reduce production cycle time, minimize analytical time and cost, augment material throughput and provide improved sensory characteristics control. Electronic nose could be considered to be used as real-time system for food quality monitoring in drying technology. As well, the further advances in electronic nose and sensor technology along with high capability of newer computerized system and new materials will show many interesting and promising perspectives in monitoring, controlling and automating of food dryers. One attractive vision for the future would be to have a fully automated platform consisting of various kinds of sensors and instruments to monitor the substantial information needed for the identification of quality of the raw material, process or product (Ghasemi-Varnamkhasti & Forina, 2014; Ghasemi-Varnamkhasti, Mohtasebi, Rodriguez-Mendez, et al., 2011; Ghasemi-Varnamkhasti, Mohtasebi, Siadat, et al., 2011). Electronic nose would make up a very important part of such a multisensor system. The artificial olfactory microsystem (electronic mucosa), as a novel technology, imitates the fundamental structure of the mammalian olfactory system to provide spatial and temporal chemosensory information. With regard to the advantages of electronic mucosa compared with electronic nose, it is hoped that this innovative tool would be employed in food drying in the close future. However, there is much research still to be carried out more particularly with regard to sensors technology, data processing, analysis of results, and validation studies. This may be realized in the drying technology in coming future.

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**Fig. 6.** Dual-column concept with large sensor arrays designed by Che Harun, Covington, et al. (2009), Che Harun, Taylor, et al. (2009), (with kind permission from Che Harun, Covington, et al. 2009, Che Harun, Taylor, et al. 2009).


