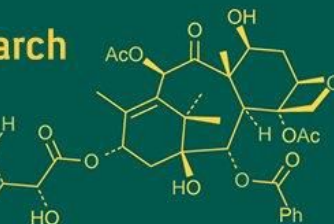
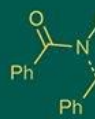
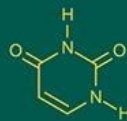
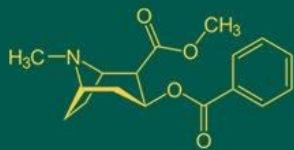


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Vaibhav Jadhav
College of Food Technology,
VNMKV, Parbhani,
Maharashtra, India

RB Kshirsagar
College of Food Technology,
VNMKV, Parbhani,
Maharashtra, India

Amol Dukare
College of Food Technology,
VNMKV, Parbhani,
Maharashtra, India

Corresponding Author:
Vaibhav Jadhav
College of Food Technology,
VNMKV, Parbhani,
Maharashtra, India

Application of electronic nose, tongue and eye in food safety and quality evaluation: A review

Vaibhav Jadhav, RB Kshirsagar and Amol Dukare

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Abstract

The paper explores the challenges faced by the agri-food sector in meeting consumer demands for innovation and technology in food production and preservation. It discusses the growth of the food industry in terms of quantity and quality and the ongoing problems this presents for productivity. The paper explores how electronic nose, tongue, and eye technologies are applied to ensure food safety and quality assurance. It offers in-depth explanations of the operational principles and sensors utilized in the electronic nose, tongue, and eye devices, along with their diverse applications within the food industry. It underscores the fusion technique, amalgamating electronic nose, tongue, and eye systems as a comprehensive quality assessment tool in the food sector, highlighting their significance in enhancing product safety, quality, and consumer confidence. It discusses the potential for future advancements in electronic sensing technologies within the food industry, including the integration of artificial intelligence and IoT devices for more sophisticated applications. The operational principles, applications, and constraints of the sensors utilized in electronic sensors were introduced and contrasted. The paper delves into the challenges and opportunities associated with the widespread adoption of these technologies, paving the way for innovative solutions in food safety and quality assurance.

Keywords: Electronic sensors, electronic eye, electronic nose, electronic tongue food safety & quality

Introduction

The food industry has grown significantly in the last few decades in terms of both the quantity and quality of food manufacturing and distribution. The demand of consumers who prioritise using innovative technologies to preserve and increase their competitiveness presents ongoing and growing problems for the productiveness of the agri-food business (Ordoñez-Araque *et al.*, 2020) [1]. A crucial aspect of the automation of the food operation is electronics. Depending on the category of food or the maker's specific demands, automated food production systems exist in a variety of sizes and features. (Handa and Singh, 2018) [2]. Sophisticated chemical and physical sciences, together with the conceptual combination of microprocessors, computers, and statistics, provide electronic sensors. These are restricted sensing materials that are mounted on piezoelectric platforms, resistive, electrochemical and optical. The electronic nose, tongue, and eye are used to analyse complex sensory input and identify features important to sensory profiles. These technologies help in many phases, from ripening to harvest, raw material storage to packaging, and consumption. This multimodal method more accurately captures the complexity of how people perceive various stimuli. Since it can become subjective due to several factors, this technology gives us access to objective data.

The food industry has been greatly enhanced by integrating electronics, leading to improved efficiency, safety, and quality. Automation powered by advanced electronic systems has completely transformed production processes, resulting in better food quality and uniformity. Sensors and biosensors driven by cutting-edge electronics provide unmatched accuracy and speed in identifying pollutants and assessing food quality, enhancing food safety and confidence for both producers and consumers. The affordability of electronic solutions has made sophisticated monitoring and quality improvement tools more accessible, promoting economic and environmental responsibility. The integration of electronics in food production fosters innovation, giving rise to novel technologies like electronic tongues and noses that revolutionize freshness and quality assessment processes.

This transformation driven by electronics promises unparalleled quality assurance, stringent safety standards, and increased efficiency in the future of the food industry. (Singh *et al.*, 2015) [4].

Electronics in the food industry are expected to have a revolutionary impact in the future, with ongoing innovation and integration spanning multiple aspects of food production and safety. The advancement and implementation of Internet of Things (IoT) devices and sensors is a significant aspect. With the ability to provide real-time data on several parameters including temperature, humidity, and inventory levels throughout the food supply chain, these devices will only grow more commonplace. In addition to increasing productivity and lowering waste, this real-time monitoring will guarantee the quality and safety of food products. Furthermore, more advanced data analysis and predictive modelling in the food industry will be made possible by developments in artificial intelligence (AI) and machine learning. AI systems can analyse large volumes of data to forecast equipment breakdowns, improve production processes, and even predict customer preferences (Baldwin *et al.*, 2011) [3].

Electronic nose

The human nose serves as a practical analytical tool for detecting potentially harmful gases in the environment and assessing food quality based on scent. Sensory panels, comprised of trained or untrained individuals, evaluate various products solely based on scent through questionnaires. Despite having 400 scent receptors and the ability to detect over a trillion smells, the human nose has limitations. Its ability to detect harmful gases is limited, and individual perceptions of scents can be biased. Additionally, the human nose cannot universally classify and discriminate between all smells due to its constraints (Bushdid *et al.*, 2014) [6].

An electronic nose, or e-nose, is a gas sensor array that responds to particular volatiles with a fingerprint. Pattern recognition algorithms, such as artificial neural networks (ANN), can utilize this data for differentiation and categorization. An electronic nose's sensing-interpreting-discriminating mechanism duplicates human olfaction.

Usually, when volatile molecules react with the gas sensor's sensing components, conductivity and other electrically associated characteristics are permanently altered. Pattern recognition algorithms then identify and characterise these variations to classify or discriminate. Compared to conventional gas diagnostic tools such as Fourier transform infrared (FT-IR) spectroscopy, high-performance liquid chromatography (HPLC), and GC-MS, e-nose is a less expensive and time-consuming method. E-noses provide more consistent measurements across devices and are less biased than sensory panellists (Tan and Xu 2020) [7].

Working principle of electronic nose (Handa and Singh, 2018) [2]

An electronic nose's operation is based on the human olfactory system.

- **Sensing System:** Electronic noses are made up of sensor arrays that can identify and examine volatile substances or smells in the surrounding air. These sensors work similarly to the nose's olfactory receptors.
- **Signal Detection:** Upon exposure to a sample or smell, the sensors in the electronic nose identify the volatile

components and produce signals in response to their interactions with the sensor surfaces.

- **Signal processing:** After the sensors produce their signals, a signal processing system processes them and turns the sensor responses into digital data that can be analysed.
- **Pattern Recognition:** Based on the different sensor responses of each scent or volatile component, various odours are identified and categorised using pattern recognition algorithms that analyse the digital data collected from the sensors.
- **Output:** Based on the pattern recognition analysis, the electronic nose produces an output or response that indicates whether or not a certain odour or compound is present in the sample.

Electronic noses are useful tools for applications such as food quality assessment, environmental monitoring, and safety inspections. They work by combining sensor technology, signal processing, and pattern recognition algorithms to effectively detect and differentiate between various odours or volatile compounds.

Sensors of electronic nose

Gas sensors can be categorised according to the sensing materials used, including conducting polymers (CP), metal-oxide-semiconductor (MOS), quartz crystal microbalance (QCM), and surface acoustic wave (SAW) sensors (Wilson, 2012). Conductivity is one of the sensors' reversible electrical behaviours, which is induced when the target gases contact with the sensor materials. Typically, the sensor's conductivity is determined by measuring its output voltage. The features of the output voltage pattern, such as voltage peak, response time, and recovery time, help to determine the sensor's functionality.

Metal oxide semiconductor (MOS) sensors

MOS is the most popular technology for electronic noses. Metal oxides (MOS) or semiconducting materials, such as tin, zinc, iron, titanium, nickel, and cobalt oxide, are the most prevalent MOS sensing materials. Alumina is one type of ceramic substrate that is covered with sensing materials. A heating element is typically included with the gadget (Burgués and Marco, 2018) [9]. Gas sensors are categorized into two groups depending on the sensing material utilized: n-type sensors, composed of zinc, tin, or iron oxides, are primarily responsive to reducing agents like H₂, CH₄, CO, C₂H₅, or H₂S. On the other hand, p-type sensors, constructed from nickel or cobalt oxides, are mainly responsive to oxidising agents such as O₂, NO₂, and Cl₂ (Nazemi *et al.*, 2019) [10].

Alcohols (such as 1-hexanol and ethanol), organic acids (such as butyric acid and acetic acid), sulphides (such as dimethyl sulphide), alkanes (such as hexane), esters (such as ethyl ester), aldehydes (such as benzaldehyde and nonanal), and ketones (such as acetone, butanone, and propyl decanoate) are some food-derived volatile compounds that can be detected by MOS sensors (Tan and Kerr, 2018) [11].

Commercial MOS sensors vary in their detection thresholds, typically ranging from 1 ppm to 1000 ppm as indicated by top industry manufacturers. Nazemi *et al.* (2019) [10] pointed out a significant limitation of MOS sensor arrays: they require operating temperatures between 150 and 400 °C, which demands substantial energy consumption and

considerable time for preheating before they become operational for measurements.

Conducting polymer (CP) sensors

CPs, also known as intrinsically conducting polymers or ICPs, consist of conducting particles dispersed within an insulating polymer matrix, including polypyrrole, polyaniline, and polythiophene (Megha *et al.*, 2018) [12]. Previous studies have indicated that CP gas sensors are widely recognized as the second most utilized gas sensors following MOS sensors. When exposed to chemical vapours, CP gas sensors undergo reactions with the sensing materials, leading to doping and subsequent changes in conductivity. This modulation in conductivity is attributed to the movement of electrons to and from the analytes within CPs. CPs exhibit notable sensitivity to a diverse array of volatile compounds found in food products, such as acetates, alcohols, and aldehydes from pears, as well as ammonia from food spoilage. Additionally, they demonstrate sensitivity to alcohol in beverages (Péres *et al.*, 2012) [13] and alcoholic volatile organic compounds associated with spoiled beef. Conducting polymer (CP) gas

sensors consume less power than metal-oxide sensors, don't need heating, synthesized easily, modifiable, transportable, robust, but require controlled humidity environment (Megha *et al.*, 2018) [12].

Acoustic wave sensors

A basic acoustic wave sensor is made up of two interdigital transducers (one input and one output), a piezoelectric substrate (quartz crystal, ZnO, or lithium niobite), and sensing material (polymeric film) (Go *et al.*, 2017) [14]. Acoustic waves are produced when the piezoelectric substrate undergoes compression or shear deformation caused by voltage, and these waves travel through the substrate. The mass of the sensor's gas-sensitive membrane changes as a result of the reaction between the sensing material and a compatible analyte, changing the SAW attenuation and velocity. the impact of mass change on the SAW in conjunction with other variables like variations in mechanical (such as viscosity and elasticity), electrical (such as conductivity and permittivity), and environmental (such as temperature and humidity) conditions.

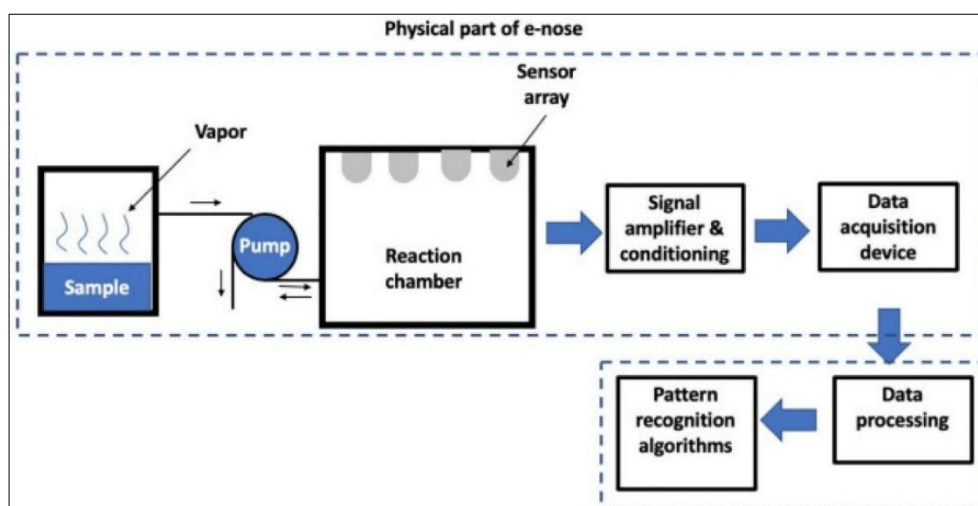


Fig 1: Operational mechanisms of an electronic nose (Tan and Xu, 2020) [7]

Applications of electronic noses in the food industry

Beer

E-nose is used to recognise and describe the key variances between beer samples. Electronic noses with sensors are used to find effective beer-making technologies (Ghasemi Varnamkhasti *et al.*, 2011) [15]. A framework utilizing gas chromatography-ion-mobility spectrometry (GC-IMS) is employed to evaluate the levels of diacetyl and pentanedione, which are byproducts of beer fermentation, and to oversee the brewing procedure.

Fish

A key quality factor that determines whether a fish is accepted or rejected is its smell. Fish and fish products are typically evaluated for quality using gas chromatography or sensory evaluation. Therefore, the creation of an effective method to regulate the quality of fish products is required. Electronic noses are crucial because they offer quick, automated, and impartial methods for evaluating the quality of fish products. Using the marker trimethylamine, electronic noses have been used to identify cod waste (Winquist *et al.*, 1995) [16].

Meat

The shelf life of roast chickens packed in a changed atmosphere has been tested using electronic noses. The results are compared with those obtained from gas chromatography, microbiological and sensory analysis. There was a strong association observed between the outcomes of the electronic nose and the microbiological analysis (Winquist *et al.*, 1993) [17].

Oil

Olive oil fragrance detection and originality verification are made possible with the application of electronic noses. Geographical location, olive seed choice, and farming practices all affect olive oil quality characteristics. An electronic nose can also be useful in determining how much an edible oil has oxidised.

Fruit

Fruits are a source of volatile substances that give them their distinct scents and special flavour attributes. In commercial fruit markets, consumer acceptability is mostly determined by fruit scent and flavour attributes. Individual preference

changes during fruit ripening are also tracked with the aid of an electronic nose. Electronic nose analysis can determine the quality of fruits by identifying changes in flavour that occur during the ripening process (Zhang *et al.*, 2008). To do this, a certain substance that aids in maturing detection was applied to the sensors of an electronic nose. By using this method, apples might be ordered based on their level of preparation. The electronic noses make it simple to determine how long to store something after it has been harvested.

Tea

According to Arshak *et al.* (2006) ^[20], an investigation into the use of electronic nose technology was carried out to improve the quality of tea.

Electronic tongue

The electronic tongue, unlike its biological counterpart, offers heightened sensitivity, selectivity, and multiplexing capabilities compared to modern biosensors. This advancement allows it to swiftly and accurately evaluate sample quality, proving invaluable across industries such as food, cosmetics, pharmaceuticals, and environmental monitoring. Comprised of multiple sensors reacting to chemical solutions, the e-tongue consists of a measuring module, an electrochemical cell (sensor array), and pattern recognition capable of identifying both simple and complex molecular systems constituting taste (Surányi *et al.*, 2021) ^[21].

As a result, the electronic tongue unravels a sample's constituent parts to extract a signal signature. An electronic tongue can describe the flavour of complicated liquids or samples that have been transformed into liquid form. The primary objective of this technology is to analyse food using a variety of sensors and then conduct statistical analysis. As such, data regarding ripeness and degree of development can be acquired (Tahara and Toko 2013) ^[22].

The E-tongue's sensor array quickly produces multidimensional information, allowing technology to identify the many patterns of chemical classes that give flavours. Multivariate statistical analysis is then used to process the complicated data produced by the E-tongue measurement. In contrast, the mechanism by which humans perceive taste and flavour also involves matching signals from taste buds with memories to identify the flavour and taste. Also, an E-tongue sensor suite can employ a broad range of chemical sensors, including mass, enzymatic, optical, and electrochemical ones.

Working principle of the electronic tongue (Handa and Singh, 2018) ^[2]

- **Taste Sensors:** An electronic tongue is made up of a variety of sensors that replicate human taste buds and are capable of identifying flavours such as umami, sour, salty, bitter, and sweet.
- **Taste Detection:** The taste sensors on the e-tongue interact with the molecules in the sample upon contact, producing signals that are contingent upon the flavour components identified.
- **Signal Processing:** A signal processing system translates the sensor responses into digital data for analysis by processing the signals produced by the taste sensors.

- **Pattern Recognition:** To identify and categorise the various taste components contained in the sample, the digital data gathered from the taste sensors is examined using pattern recognition algorithms.
- **Output:** The electronic tongue indicates the makeup of the flavour components in the sample with an output or response based on the pattern recognition analysis.

Sensors of electronic tongue

Taste sensors

Optical mass sensors, biosensors, and electrochemical sensors are examples of chemical sensors that are frequently used for an electronic tongue. Chemical sensors in electronic tongues, like gas sensors in electronic noses, react with analytes to cause reversible changes in electrical properties. Pattern recognition and categorization are performed using measurable electrical signals (Podrazka *et al.*, 2017) ^[24].

The chemical composition of flavours activates the sensor, revealing taste interactions such as suppression effects seen in mixtures of bitter and sweet substances. For instance, sucrose reduces the bitterness of quinine and certain drugs. By analysing sensor outputs and flavour profiles, amino acids can be categorized. The taste sensor evaluates the flavours of various foods like beer, coffee, mineral water, milk, sake, rice, soybean paste, and vegetables, providing an objective means to assess human sensory perception. Combining conductive polymer components enables the differentiation of wine flavours by integrating taste and odour sensations (Moon *et al.*, 2020) ^[25].

Potentiometric chemical sensors

Most electronic tongues rely on potentiometric chemical sensors, which gauge the voltage difference between the working electrodes and a reference electrode. In this setup, the reference sensor voltage remains steady as the reference electrode sits in an electrolyte solution. The voltage of the working electrode varies based on the concentration of the analyte in the solution. Glass, liquid, solid-state crystalline, and polymer membranes (such as polyvinyl chloride) are the most often utilised membrane types for potentiometric chemical sensors. Silicate glass, which is typically used to detect acidic or alkaline pH, served as the model for the glass membrane electrodes. Silver chloride and other inorganic salts make up the solid-state crystalline membrane. When an ion exchanger or ionophore is dissolved within a dense organic membrane, it forms a liquid membrane. In contrast, polymer membranes typically consist of PVC, plasticizers, and an ion exchanger. Liquid membrane electrodes are commonly utilized for calcium measurement, while polymer membrane electrodes are often employed for measuring ions such as potassium, calcium, and chlorine (Borges *et al.*, 2018) ^[26].

Voltammetric chemical sensors

Voltammetric instruments drive electron transfer reactions through electrode potential, unlike potentiometric methods. Analyte reduction and oxidation generate a current, which is measured. The simplest setup involves three electrodes: reference, working, and auxiliary. Metals like copper, gold, platinum, and others are commonly used for electrodes. Voltammetry entails submerging a multisensor matrix in the solution to be measured. By exposing the working electrode to a step potential, polarization currents across different

solutions are assessed, enabling comprehensive qualitative and quantitative analysis of sample attributes.

The step potential applied to the electronic voltammetry tongue (VE tongue) incorporates two primary pulse types: a large conventional pulse and a multi-frequency pulse. Pulse voltammetry, particularly large amplitude pulse voltammetry (LAPV) and small amplitude pulse voltammetry (SAPV), is commonly used for VE tongue analysis. Various studies have utilized voltametric electronic tongues for tasks such as detecting adulteration in argan oil with sunflower oil, monitoring the quality and shelf life of unsealed pasteurized milk, distinguishing between different floral varieties of honey, and assessing quality parameters in spring water. (Pein *et al.*, 2015) [28].

Bioelectric sensors

Active components of biosensors, such as biological sensing elements, play a crucial role in achieving high sensitivity,

selectivity, and specificity when detecting bioactive analytes. Bioelectric sensors rely on biomaterials as sensing materials. These sensors, including voltametric, impedimetric, potentiometric, and conductometric varieties utilized in electronic tongues, commonly employ biological materials such as enzymes, whole cells, tissues, receptors, or antibodies (Li *et al.*, 2019) [29]. The operation of these sensors typically involves a series of biological reactions leading to the transfer of electrons, ions, or molecules, such as enzyme-substrate interactions. Various food components like acids (e.g., lactic, acetic, sialic acid) and sweeteners (e.g., glucose, lactate, sucrose) are essential, and voltametric bioelectric sensors are frequently employed to analyze their properties. By directly binding target bacteria or immobilising a target microorganism's metabolites, they are also frequently employed to detect the growth of microorganisms (Miao *et al.*, 2017) [30].

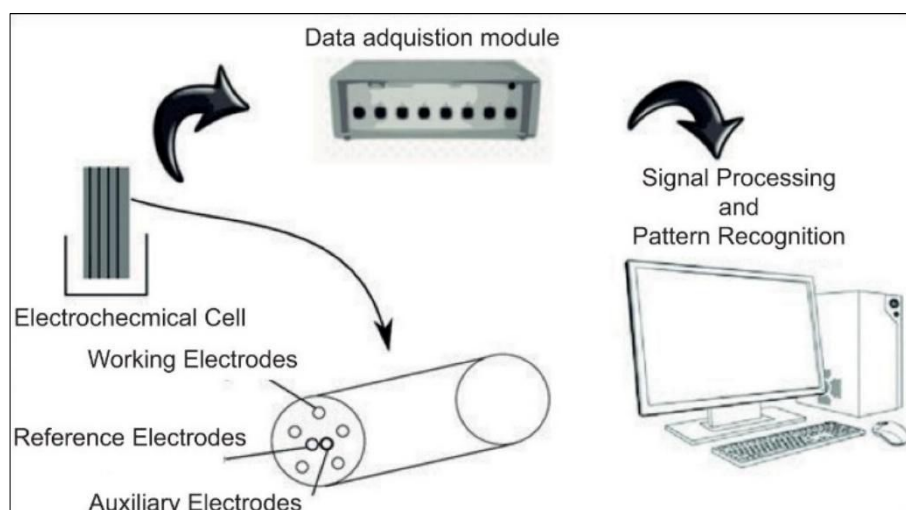


Fig 2: Operational mechanisms of an electronic tongue (Leon-Madina *et al.*, 2019) [50].

Application of the electronic tongue in the food industry

Dairy industry

Research has indicated that the "e-tongue" has several uses in the dairy sector, including sample classification, identifying the substances that cause aroma degradation, assessing microbiological quality, detecting mastitis, identifying antibiotic residues, adulterating milk, and more. "E-tongues have been extensively studied for their ability to qualitatively analyze milk and fermented milk samples, with a focus on identification, classification, and recognition. In a study by Winqvist *et al.* (2005) [33], these devices were integrated into dairy industry processes. The results indicated promising potential for distinguishing milk from different sources and assessing its quality." According to these studies (Dias *et al.* 2009) [34], there is a chance that e-tongues will be a useful security tool to stop financial losses that could arise from contaminated raw milk. Studies have also demonstrated the capability of monitoring raw milk. The milk quality degradation that results from microbial growth in room-temperature storage is observed by Winqvist *et al.* (1998) [35] using an e-tongues measurement principle based on pulsed voltammetry. The acquired data were analysed using Principal Component Analysis, and Artificial Neural Networks-which have been shown to accurately forecast the trajectory of bacterial development in

milk samples-were employed to create prediction models (Winqvist *et al.* 1998) [35].

Meat industry

To assess the freshness of pork, Kaneki *et al.* (2004) [36] developed the "e-tongue," which uses potentiometric solid-state electrodes. Researchers utilized solid-state electrodes such as Pt, CuS, and Ag₂S electrodes to identify the organic compounds generated during the initial phase of meat decomposition, including putrescine and dimethyl sulphide. Variations in chemical compositions and flavours were observed among different cattle breeds, as reported by Zhang *et al.* in 2015 [37]. The "e-tongue" system was able to quickly identify several beef breeds based on their flavour qualities, as demonstrated by PCA analysis, which also clearly separated the various breeds of cattle. Furthermore, "e-tongue" could be utilised to forecast the chemical composition using the regression formula that links flavour and chemical composition.

Assessment of coffee and tea: Organoleptic features play a vital role in coffee quality assessment, influenced by cultural expertise and production challenges like diseases and climate. E-tongues offer efficient, objective classification, as demonstrated by Almario *et al.* (2014).

Wine production application

The development of e-tongues, which are equipped with 23 potentiometric chemical sensors, was utilised to distinguish and evaluate Italian wines qualitatively. The "e-tongues" were able to discriminate between wines produced at various vineyards within the same vintage and wines from different geographic regions. Moreover, the electronic tongue could assess the flavour attributes of wine using intricate scores akin to those produced by human tasters. Parra *et al.* (2006) researched tailor-made electronic tongues featuring a mixed sensor array comprising voltammetric electrodes chemically modified with various electroactive substances, such as polymerized pyrrole solutions doped with six different agents. This setup aimed to differentiate and identify characteristics among 12 Spanish red wines, including vintage, grape variety, denomination, and origin.

Electronic eye

An electronic eye, known as a computer vision tool, transforms optical images into digital format using an image sensor and computer algorithms for objective image analysis (Xu, 2019) [38]. The process involves five fundamental steps: image capture, image processing, feature extraction, pattern identification, and decision-making. These steps can be represented sequentially in a flowchart. Decision-making in computer vision involves predetermined rules within the control system, which may require adjustments based on optimization criteria and interaction techniques (Bhargava and Bansal, 2018) [39]. Computer vision is a crucial component of intelligent control systems, which may incorporate supervised or unsupervised learning for tasks such as pattern recognition, modeling, and knowledge base construction.

Working principle of an electronic eye (Handa and Singh, 2018) [2]

- **Image Capture:** An electronic eye uses sensors like charge-coupled devices (CCDs) or complementary metal-oxide-semiconductor (CMOS) sensors to capture visual information, just like a human eye does. By

converting light into electrical signals, these sensors produce a digital image of the scene.

- **Image Processing:** After the picture is taken, the electronic eye uses software and algorithms to process the digital data to extract pertinent features, improve image quality, and correct distortions. Colour correction, image sharpening, and noise reduction are a few examples of image processing techniques.
- **Feature extraction:** It is the process of identifying particular characteristics or interesting patterns, like edges, forms, textures, or colours, from the processed image data. To facilitate subsequent analysis, this stage entails locating and emphasising important components within the image.
- **Object Recognition:** The electronic eye can identify and categorise items in a visual scene by comparing the extracted features with preset patterns or templates. Using visual cues, object recognition algorithms assist in identifying and distinguishing various objects or entities.

Sensors of electronic eye

CCD Sensors

Digital cameras have long utilised CCD sensors, a more conventional kind of image sensor. Through the conversion of light into electrical charges, which are subsequently transmitted and read out pixel by pixel, they function. High-end digital cameras frequently have CCD sensors because they provide exceptional image quality, particularly in low light.

CMOS Sensors

Compared to CCD sensors, CMOS sensors feature cheaper production costs, faster readout rates, and lower power consumption, which has led to their rising popularity in recent years. CMOS sensors function by directly turning light into electrical charges at each pixel, doing away with the requirement for an additional charge-transfer device. Smartphones, action cameras, DSLRs, and other types of digital cameras frequently contain them.

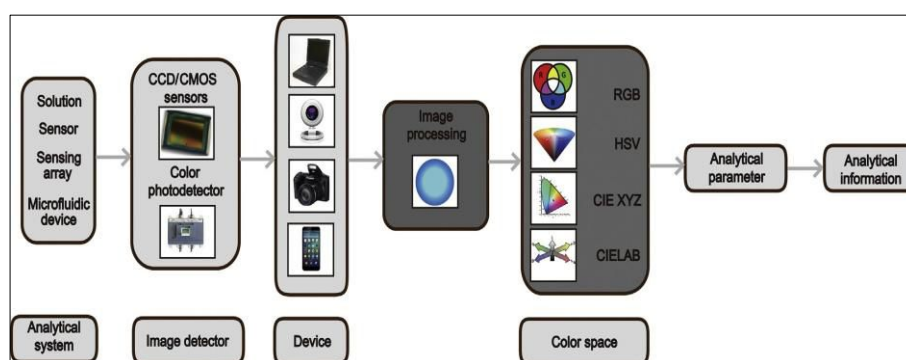


Fig 3: Operational mechanisms of an electronic eye (Xu, 2019) [38].

Application of the electronic tongue in the food industry

In food operations, the electronic eye has shown to be a flexible and invaluable tool, providing quick, precise, and non-destructive means of detecting and assessing product quality. It enables thorough monitoring of shape, size, colour, and texture analysis by combining several disciplines, including mechanics, optics, electromagnetic detection, colourimetry, and image processing. Most importantly, according to Ordoñez-Araque

et al. (2020) [1], its objectivity and dependability allow for repeatable tests, guaranteeing constant product quality and traceability.

The electronic eye has the advantages of speed, ease of use, and versatility, enabling comprehensive analysis without the need for sample preparation or size restrictions. Its uses are widespread in the agricultural and food industries, supporting the categorization, qualification, and observation of product ageing, fermentation, and colour changes that

occur throughout processing stages such as cooking, frying, or freezing. Specifically, it allows for automation solutions to optimise product lifetime in the brewing industry (Orlandi *et al.*, 2019; Yasui *et al.*, 2019) [45, 46].

Fusion technique

Three analytical systems known as electronic nose (e-nose), electronic tongue (e-tongue), and electronic eye (e-eye) are commonly employed for quality evaluation purposes within the food and pharmaceutical industries (Kakani *et al.*, 2020; Karakaya *et al.*, 2019) [52, 53]. Combining these three technologies yields a nondestructive, rapid, consistent, and cost-effective inspection method. This integrated approach offers a versatile tool for assessment, surpassing individual techniques in performance. Kiani *et al.* (2016) [54] propose a

range of applications for this integrated assessment approach, which can effectively replace systems lacking adequate performance for specific tasks.

Emerging technologies that integrate artificial senses have demonstrated the potential to deliver precise results more rapidly compared to standalone sensors (Apetrei *et al.*, 2010) [43]. The utilization of multivariate analytical approaches in conjunction with objective sensing mechanisms has shown remarkable effectiveness. Significant efforts have been directed towards developing various data fusion techniques in recent years. These methodologies amalgamate data from multiple instrumental sources to improve the assessment of food quality (Di Rosa *et al.*, 2017) [55].

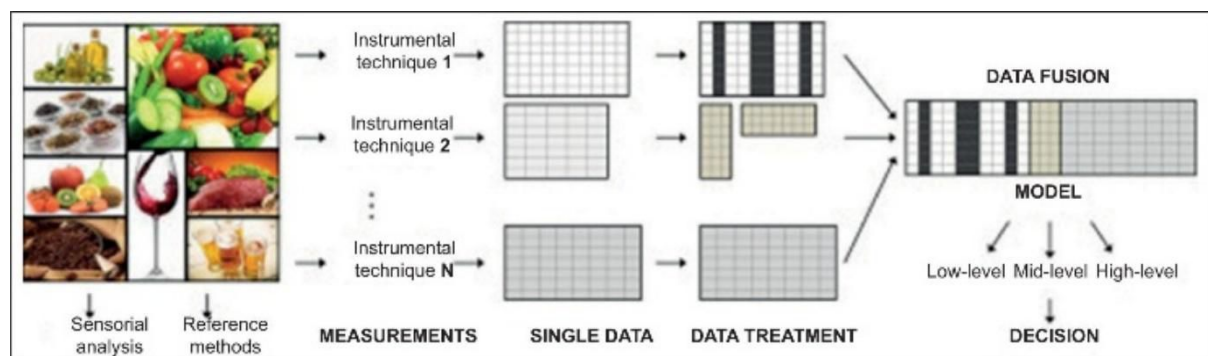


Fig 4: Methods of combining data in the evaluation of food quality (Borras *et al.*, 2015) [57]

Table 1: Applications of fusion approach in food quality assessment (Kiran *et al.*, 2022) [58]

Sample	Quality Parameter Observed	Fusion Method Employed
Fruit juices	Juice Classification	Integration of E-nose and E-tongue
Fish	Freshness, Firmness, and Quality Evaluation	Fusion of Computer Vision System and NIRS
Honey	Botanical Origin Identification	Combination of Potentiometric Electronic Tongue and CVS
Packaging remnants	Safety Assessment of Former Food Products	Coupling of Stereomicroscopy with Computer Vision System
Pork	Total Viable Count Quantification	Integration of Hyperspectral Imaging with Colorimetric Sensors
Pork	Total Volatile Basic Nitrogen (TVB-N) Detection	Fusion of Hyperspectral Imaging with Odor Imaging Sensors
Pork	Freshness Indicator	Utilization of NIRS and MSI
Pork	Freshness Evaluation	Combination of NIRS, CV, and E-nose
Rice wine	Sensory Quality Analysis	Integration of E-eye, E-nose, and E-tongue
Chestnut	Identification	Fusion of Sensory and FTNIR Spectral Data
Brazilian monovarietal olive oil	Storage effects	Application of data fusion and chemometrics

Conclusion

Electronic sensing systems serve an important role in maintaining food quality and safety in an ever-expanding food sector. Their quick, repeatable, and compact nature fits perfectly with the fast-paced, continuous operations of food manufacturing. Integrating intelligent detection techniques with sensory and chemical analysis enhances precision in quality assessment across a wide variety of food items. From fruits and vegetables to meat and poultry, automatic classification necessitates adaptive solutions that are suited to each product's characteristics. Automation has become pivotal in food manufacturing, with electronic systems tailored to individual manufacturer requirements, ranging in size and function. These solutions simplify procedures, ensuring high quality while increasing overall efficiency.

Finally, a partnership between electronic sensing technology and the food business promotes product safety, quality, and customer trust. This collaboration not only encourages innovation but also improves sustainability in

food production. As the industry evolves, electronic sensing systems will remain critical instruments for maintaining food quality and fulfilling the changing needs of customers and regulatory requirements alike.

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