DELIVERABLE 4.5

FOOD MICRO SYSTEMS

DRAFT

FINAL REPORT

SYNTHESIS OF THE ROADMAPS FOR THE IMPLEMENTATION OF MICROSYSTEMS IN THE FOOD AND BEVERAGE SECTORS

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SEVENTH FRAMEWORK PROGRAMME

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FoodMicroSystems aims at initiating the implementation of microsystems & smart miniaturised systems in the food sector by improving cooperation between suppliers and users of microsystems for food/beverage quality and safety.

The project runs from September 2011 to November 2013, it involves nine partners and is coordinated by ACTIA (Association de Coordination Technique pour l'Industrie Agro Alimentaire, France). More information on the project can be found at http://www.foodmicrosystems.eu.

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1 Introduction

The main ambition of the *FoodMicroSystems* project was to stimulate the implementation of innovative solutions based on MicroSystems Technology (MST) in the food sector. Previous reports from the project analysed the demands from the food sector and the technologies available from the microsystems community. These reports indicate that there is significant potential for innovation based on MST: the food sector needs technological innovation to meet its future challenges - this demand for solutions to guarantee food quality and safety and to better control food processes is expected to increase in the coming years. The microsystems technological area has the capacity to meet these demands by offering a wide range of new solutions for processing, measuring, sensing, tracking or tracing.

Building on the findings from the reports on the market demand and the technologies available, three roadmaps have been elaborated. The roadmap reports identify the developments necessary to bring MST-based solutions into three main sectors: the dairy, the meat and the beverage (wine and beer) food industry. The reports provide a review of the supply chain and of the main drivers for innovation in each sector as well as technology-to-application roadmaps for implementing MST-based solutions in several areas:

- Safety, process and quality control, cleaning and maintenance, and microfiltration for the roadmap on the dairy sector.
- Process control, safety and authentication, robotics for worker assistance, home cooking devices for the roadmap on the meat sector.
- Quality and authentication of raw materials, quality markers for the fermentation process, process control, logistics and product authentication, safety and environmental control for the roadmap on the wine and beer sector.

This final (technology) roadmapping report builds on the previous reports and complements the findings of the three application roadmap reports by providing suggestions to address the technological needs in three main opportunity areas identified across the three application roadmaps: gas, chemical and biochemical sensors & sensing systems, microorganism detection and tracing & tracking systems.

Each section contains information on the types of devices that are needed as well as a roadmap for guiding the technological developments within the next 3 to 10 years. The report starts with a review of the demand and the offer for microsystems in the food sector. It also includes a business case to illustrate how a company can successfully take advantage of microsystems developments in the food sector.

2 Microsystems in the food sector: technology-push versus market-pull

Food is an application sector for modern technologies with characteristics that are much different from other industry sectors: Food is a basic "pillar" to life that everybody needs to survive and lead a healthy life – in the more developed Western world, food also is a distinction for the "quality of life". Overall, food is the most frequently used consumer goods. Apart from the physiological aspects food has cultural, emotional and societal aspects that all play an important role in how we experience food, what we expect from it and what we are likely to accept. Compared to many other frequently used goods, the emotional attachment towards food is much higher.

Consumers expect their food to be healthy, safe and of good taste. In addition food should have a pleasant texture, be easy to prepare, provide pleasant sensations, and should be storable for prolonged periods. Beyond these functional and sensory experiences in the past decades a number of additional demands have evolved especially in industrialised societies: food must be natural, should be produced in a sustainable way with respect for the organisms that are being used and should not, or only mildly, be conserved, etc. These demands often contradict each other. The food sector is therefore constantly looking for cutting edge compromises between these aspects. Mild conservation and prolonged shelf life in combination with safety for instance requires creative and innovative solutions. The sector uses every opportunity offered to solve some of the incompatibilities in the consumer demands. Many technologies are used in the sector to this extend.

Microsystems can definitely contribute to solutions of some of the opposing demands but haven't been used extensively in the sector for several reasons. First of all, the food sector is quite conservative in its approach to processes and product innovation. Secondly production systems are often traditional and linked to product quality and/or require substantial investments. Thirdly the regulation surrounding food production and food products, especially in Europe, is often preserving existing processes and is not in favour of innovations. For instance, if a production process is changed to a certain degree the resulting product needs re-approval by EFSA. And if a company wants to launch a new product with benefits to consumer health it is very difficult to get approval for health claims. Fourthly in view of the consumer demand for natural food, the sector is reluctant to use state-of-the-art technology because they fear that the resulting products will be perceived as technologically enhanced rather than natural and thus might be rejected by consumers. Finally profit margins on products in the food sector are typically very low, while volumes of low priced products are high – this makes the implementation of high-tech innovations problematic from an economic point of view.

Microsystems have predominantly evolved in sectors that are more technology inclined than the food sector and have demonstrated very specific advantages, which can now also be used in the food sector to address some of the challenges. Electronic and communication systems have demonstrated that complex systems with high levels of functionality can be produced cost effectively. Applications in process control have shown that systems can contribute to better control of processes and product quality and at the same time can make processes more sustainable. Medical applications have proven that the safe use of these systems at and in human beings is absolutely feasible. Acceptance of large scale implementations of microsystems in everyday products like mobile phones and computers have assured that consumer acceptance is possible as long as end-user benefits are explicit and important.

One of the challenges of adopting microsystems in the food sector is that the MST technology providers and the food industry are not well aligned. In first instance the technology providers, often SMEs, have focussed on sectors with large margins for their primary applications and have developed their products in these directions. They are not very familiar with the typical procedures and problems that are associated with food production. They also speak a different 'language' than the people in the food industry. The food production companies on the other hand, with their conservative attitude that originates in the recognition of the importance of tradition, the regulatory problems associated with changes and the fear of rejection by consumers, have been wary of new technologies and the potential they represent. But times are changing and the challenges industry and society are facing no longer allow ignoring the opportunities of microsystems in the food sector. The traditionally very closed food sector no longer can ignore the potential of open innovation, which has shown to be very powerful in many other sectors, and will adopt cross-disciplinary collaborations with other sectors, including the MST companies.

One of the characteristics of the food sector is the complexity of supply chains. In recent years it has unfortunately become clear that this complexity can compromise the quality of food products. Consumers are more and more requesting that food chains become more transparent, offering information about e.g. the origin and authenticity of products, quality and freshness, sustainability, etc.

In recognition of the many opportunities microsystems technology can offer and the contributions it can provide to the important challenges that the food sector is facing with regard to consumer health, sustainability, economics and food security, the *FoodMicroSystems* project was eager to find ways in which the possibilities of the technology can be aligned with the demands from consumers and the food industry which constitute the market.

In the first phase of the project partners have looked at the developments that currently take place in the microsystem and nanotechnology field and can be expected to provide implementation opportunities also in the food sector. Key elements that were found in this phase are the many technologies that are in the pipeline for sensors and measurement & detection systems; the trends towards distributed systems that link autonomous networks; developments towards low energy applications and energy scavenging to become less dependent on external energy sources; and new technologies that diverge from silicon microelectronics and can offer low-cost and more sustainable functionality in e.g. disposable systems (packaging).

In the second phase of the project four food production value chains were examined for specific requirements. Common elements that were found are a very general demand for
(1) fast, cheap, easy to use and accurate measurement technology that provides information of food product quality and safety;
(2) sensors for process monitoring that can improve control and the quality of the end product and make the processes more sustainable;
(3) process innovations that provide higher quality products with less variability and less inputs and new products with beneficial properties; and
(4) new packaging concepts that can fulfil the consumer demands for low preservation, long shelf life and convenience.

The project also looked at the aspects that can influence consumer acceptance of products that make use of microsystems and the related ethical issues. In general it can be concluded that consumers accept applications of such technologies as long as the benefits are very clear, it doesn't increase the price (too much) and there are little risks involved. A higher price will only be accepted, if the consumer gains direct benefit in the form of a significantly better product experience. However, regardless of risk assessment, as soon as new technology is used for a product, consumers consider risks to be higher. There are also some worries about contamination from MST devices to the food product and environmental contamination after the useful life of the micro system. Consumer acceptance is mainly based on perception of technology attributes, which is only for a small part related to formal assessment of the (positive and negative) impact of a technology.

In a synthesis from these three different views and to stimulate the development of new applications of microsystems in the food sector, overall four roadmaps have been drafted. The aim of these roadmaps is to align future efforts from technology providers and the research community with the demands from the food industry. By providing ambitious but attractive goals for the long term it is possible to define a trajectory with intermediate aims that not only provides interesting opportunities for the technology companies to focus their product development on, but also invites the food industry to anticipate the new capabilities in their product and process innovations. In this way these roadmaps shall contribute to the coordination of (so far) not inter-linked research and development efforts in sectors that are far apart but slowly recognise the joint opportunities when looking at the long term perspectives. Thus, the *FoodMicroSystems* results have already started to stimulate the implementation of innovative solutions based on microsystems technology in the food sector. To make sure that these roadmaps are adopted and used by both the food and the MST sectors they need to be maintained and periodically updated by the various stakeholders.

3 Chemical and Biochemical Electronic sensors and systems

In the food and beverage sectors, many of the products show an evolution during their process that can be characterized by a great number of environmental and processing parameters and by the own product aspects or attributes. Often these aspects are associated with specific chemical markers. This scenario makes it necessary to continuously measure these analytes in order to help on the process control and the decision-taking regarding the different elements of the process during the food and beverage production. At the moment, off-line measurement of these markers influencing the final product quality requires that the food and beverage producers own or have access to complex and specialised laboratories, which in most cases is not possible or fast enough. In that situation any attempt to develop new portable and on-line systems will be welcome, and the contribution of new technologies like microsystems can be of great importance.

In Deliverables D.4.2, D.4.3 and D.4.4 complete studies related to the identification of main innovation and market drivers for new microsystems solutions for the food sector have been presented. Special focus has been put on the Dairy, Meat and Beverage Sectors. In this document, the technological requirements and future developments that these microsystems have to follow will be shown in order to be real solutions.

A challenging problem in food processing industry is quality and safety of food products and thus the use of time consuming analytical tools, mostly based in complex and expensive laboratories has been a must for the food and beverage producers. Chromatography, HPLC, Mass Spectrometry, FTIR, enzymatic assays, etc. are traditional methods that can be complemented by new tools based on new technologies. In this scenario, according to COWIN[1], Smart Systems (microsystems being part of them) may play an important role to bring breakthrough innovations in the diagnostic field and reinforce European competitiveness as these technologies and devices are especially well-positioned to provide attractive solutions for on-site testing.

The industrial diagnostic sector that includes food and beverage, environment and security, is smaller than the medical diagnostic market but is representing today an attractive business opportunity for players in the field. For instance, the control of microbiological quality of food, which is only a part of the sector needs, represents a global market at 800M€, growing at 4 to 6% a year (source: bioMérieux in the Cowin report). And it is not only the biological diagnostics sector but also the process control companies that develop physical and chemical sensing systems are interested in the food and beverage sector.

[1] COWIN report – Main challenges for smart systems towards diagnostic markets

In some cases, the microsystems solution does not have to develop only the sensing part but also the sample treatment and pre-processing prior to the measurement. In these cases, microsystems technologies would encompass the microfluidics part of the test system as well. Figure 3.1 shows the Yole Développement market forecast for microfluidics /microsystems in Life Sciences also presented in the COWIN report, which indicates that there will be noticeable market growth in the near future.

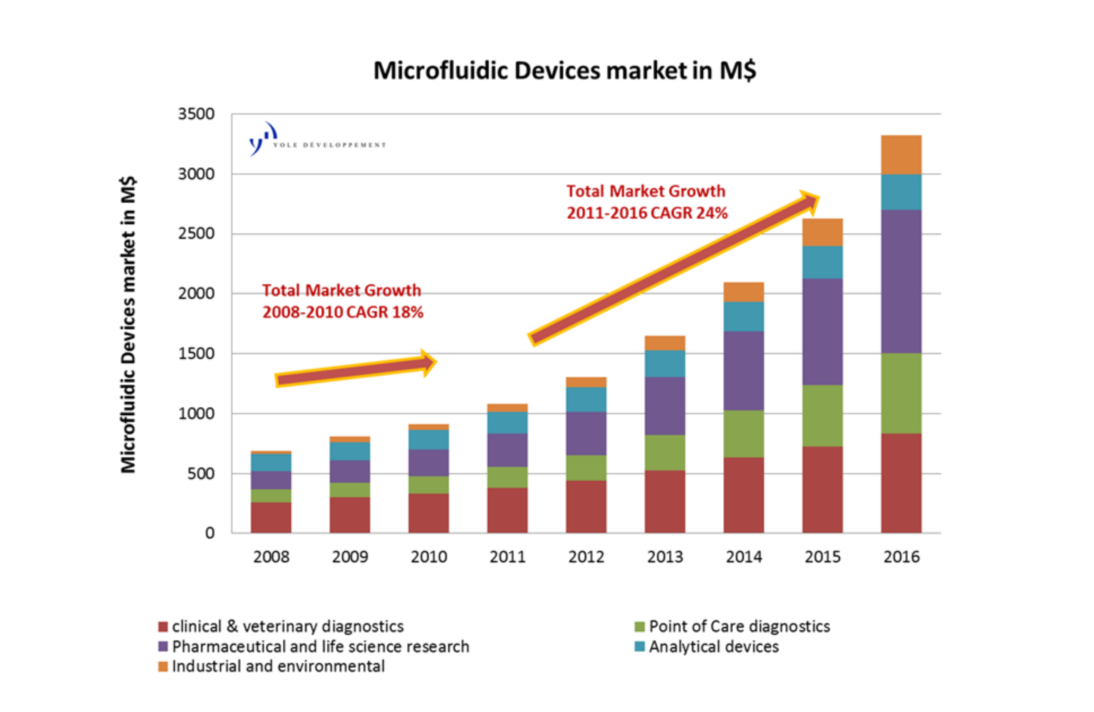


Figure 3.1: Microfluidics/Miniaturized Smart Systems market forecast in the Life Science field (source: Yole in COWIN report).

The food and beverage sector is highly regulated and it takes time for a new technology to be fully compliant and accepted by the regulatory authorities and the industrial users. The discussion carried out with representatives of food and beverage industries has shown that there is an interest of the end users to prospect all potentialities of microsystems usage is suggested in most cases not to replace already established procedures but to complement them. Microsystems can also be used to create new solutions for not yet solved problems, taking into account that cost of analysis is an issue for the sector. The use of microfluidic devices and microsystems are expected to address niche markets that may benefit from the use of a lower volume of sample and reagents, to potentially provide quantitative testing, and faster response, higher sensitivity and selectivity that classical laboratory tests. Depending on the application it is possible that all these characteristics are not necessary at the same time. Thus, future research on microsystems has to address both simple and complex systems, because of the variety and requirements of the potential applications..

In the FoodMicroSystems Deliverables Del 4.2, Del 4.3 and Del 4.4, it has been shown that the food and beverage sector is ready to accept new solutions based on sensing devices and systems of different nature, for both monitoring quality and safety of the product during processing and for optimising the production process. Such solutions could cover:

- physical sensors: temperature, pressure, ultrasounds, turbidity, colour, etc.
- gas and aroma sensors: volatiles, gases, etc.
- chemical sensors: pH, redox, specific ions, etc.
- bio-sensing systems: antibody, enzymatic, genosensors, DNA, etc.
- artificial vision: CMOS cameras and image processing
- RFID, and other traditional electronics circuits

From the point of view of the complexity and of the need of the development of microsystems technologies, these families of devices and systems do not show the same requirements. Some of them have already reached the level of development that allow them to be industrialised and some have reached the market with success for food or other applications, and in fact do not need specific long term developments for being adapted to the monitoring of the food and beverage sectors. This is usually the case for most of the sensors and sensing systems based on physical parameters.

Another group of devices can be considered not in the core of the development of novel food microtechnologies. In many cases, these systems can be already found in the market as pure microelectronics products. This is the case of standard RFID (most of them without sensing capabilities) and artificial vision systems (based on CMOS vision chips). Development activities for adapting them to the food and beverage process monitoring requirements might be enough for these solutions to become useful in the food sector.

Finally, there is the group of chemical and biochemical sensors for gases and liquids that, despite having been the focus of research in the last decades, have not reached the degree of maturity necessary for being well accepted and marketable in the food sector. Research carried out in the last years has shown that many attributes, defects, and process parameters may be monitored through the related aroma and taste of the food product. Thus, it seems reasonable that an increasing interest on solutions based on gas and biochemical measurements is developed in the future, and that systems building on these are most likely candidates for successful market introduction in the medium term. These are the systems that need additional research in the next decade and, therefore these are the systems that will be studied in this document from the microsystems technological point of view.

Solutions based on microsystems will be successful, not only if the technological challenges are reached but only if they comply with the other drivers of innovation of the food and beverage actors that we can summarise as follows:

- Assure quality and safety while optimising the production process, with a sustainable use of resources, and ensuring a low impact in the environment.
- Comply with the new regulations and the associated increase of number of tests while reducing to the maximum the increase of the production costs.

- Better manage the production by using fast analysis systems for efficient on-line testing.
- Increase the competitiveness of the company.

In the next chapters, the technological requirements for developing the main microsystems identified will be presented. To be useful, these devices will have to answer the following expectations:

- speed of the analysis, automation and simplicity of use
- autonomy and portability
- sensitivity and reproducibility at least comparable with existing solutions or with some added value
- low cost

It is possible that not all food and beverage attributes and markers demanded by the industryin the sector can be addressed with microsystems, at least in the short or medium term. The objective of the present discussions is to help on the identification of the simplest applications and the technology trends to bring real solutions to the market that may be considered as success stories and that can help on the increase of microsystems awareness and confidence of the food and beverage sector. The next paragraphs will concentrate on the most promising families of sensors and sensing systems.

3.1 Description of the devices and technology needs

3.1.1 Gas sensing devices and systems

Many quality attributes and safety problems in food and beverage products and intermediate processing steps may be monitored by detecting their associated aromas, volatiles compounds and gases.

Examples of potential use of simple sensors or more complex systems in the beverage sector are: evaluation of the aromatic richness of grapes and other raw materials, phenolic maturity of grapes, volatiles compounds during wine and beer elaboration, authentication, discrimination, antifraud of beverages, sensors for RFID, defects in corks, etc.

In the meat and dairy sectors, volatile detection is also of interest but has mainly been addressed with more complex systems like e-noses, as will be seen later.

Some gas sensing systems are available in the market for environmental, industrial safety and other niche applications. E-nose systems, which are based on gas devices, have been developed for other applications and could be adapted to the food and beverage process monitoring. However, despite the research done in recent years, commercial success and ubiquitous use has not happened so far for a variety of reasons. Cost is an issue, but especially the need of better performance in terms of sensitivity, selectivity, power consumption and long term stability and reliability are challenges that still have to be solved, probably with more an evolution than a revolution of current technologies.

In food and beverage applications we usually have a need to detect one or more components of a mixture of gases. This means that in some cases the systems to be developed may be based on single specific sensor devices, or in most of the cases, they will have to rely on a more complex combination of sensors, filters, electronics and data processing.

In this document we concentrate on microsystems solutions for:

- Single sensors
- E-nose based systems
- Micro chromatographers

Generically, it can be stated that in the food and beverage sector it is of interest:

- To use cheap single sensors or simple systems with high sensitivity to one gas, for simple single point measurements of simple gases or vapours.
- To use optical sensors and systems when more selectivity and stability are required.
- To develop and integrate multi sensing systems (e-noses…) that, with the help of data processing, may be useful in the case of detecting gases and volatile organic compounds (VOCs) in mixtures, or fingerprint such mixtures.
- To develop more advanced systems (e.g. micro gas chromatographers, Ion Mobility Spectrometers…) when high discrimination is required and not achieved with more simple systems.

Single gas sensors

Figure 3.3 summarises the main microtechnologies that have been studied in the past for gas sensors. It can be seen that there is a big variety of possibilities and sensor properties are very dissimilar for different gases and applications of the food and beverage sector, as for any other application. The low cost, fast response, long term stability required for the sensors, and the different gases and vapours to be detected make difficult to find a unique microsystems solution or even a unique solution for each marker of interest in the food and beverage sector. From what has already been studied in the last decade it can be concluded that microsystems technologies may be useful for gas sensing devices.

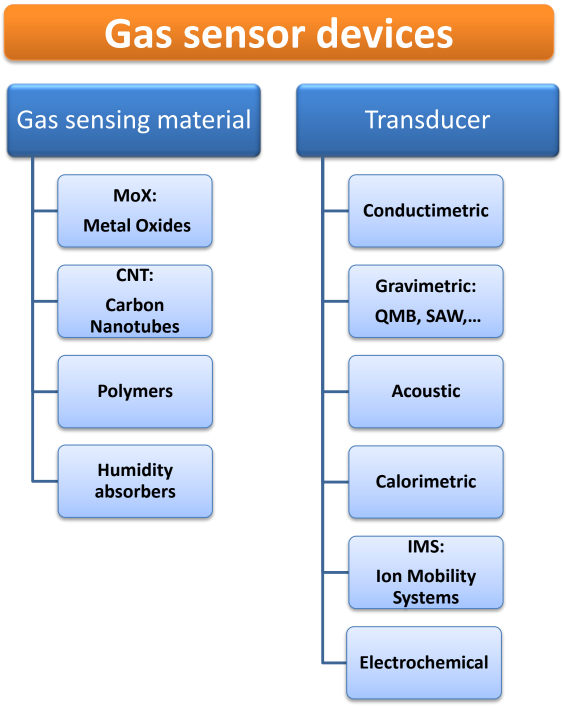


Figure 3.3: Summary of main microtechnologies and materials for gas sensors

Among the different technologies for gas sensors, Metal Oxide (MOX) gas sensors and arrays seem to be the more appropriate to meet the specifications required. For being useful in portable systems for food and beverage process control such devices have to measure at ppb level and with ultra low power (<10 mW) consumption. They can be also of low cost and be part of more complex systems like e-noses. Other interesting technologies, but less developed and more complex could be IMS (Ion Mobility Systems) and SAW (Surface Acoustic Wave) devices combined with polymers, despite they can be very valuable for some volatiles. If more selective systems are necessary, then optical devices and systems, such as Non Dispersive Infra-Red (NDIR) systems, may be more appropriate.

The advantages of Microsystems are based on the fact that microfabrication brings low cost using standard silicon technologies. Silicon's major contribution in gas sensors is its use combined with silicon micromachining techniques as a substrate for metal oxide gas sensors.

However, there are still some problems not yet solved and for the specific case of MOX and optical based sensors we can say that:

- Low power requirement (target: less than 10 mW for 550°C of operating temperature) have not yet been reached. Low power is crucial for achieving the requirements of portability and ubiquitous use of gas detecting systems. Research should continue in this direction.
- Miniaturisation is necessary for MOX systems and arrays but not always beneficial for other types of sensors (i.e. optical sensors may suffer from low

sensitivity due to the short optical paths inherent of miniaturised devices) and may give low resolution.

- Lack of enough sensitivity and specificity (has to be in the range of ppm's and below), for aromatic properties of food and beverage because of the current used sensing layers.
- Not enough repeatability on gas sensor arrays.
- Sensors sometimes need of pre-filtering and pre-concentrating devices for achieving the desired specifications, which makes it difficult the integration of operative microsystems
- Cost of gas sensors is not low enough to be broadly used.

Thus, some actions are defined for mid to long term research. For the MOX sensors point of view, some technological intermediate steps maybe defined in the following directions:

- Novel nanomaterials for increasing sensitivities.
- Novel materials for low power hotplates. E.g., porous silicon, polymer substrates.
- Novel catalysts. Novel high effective surface area sensing layers.
- Devices of smaller dimensions and ultra low cost: CMOS.
- CMOS compatible process integration or methods for growing nanomaterials as a post CMOS step.
- New electronic circuits and methods for reading the resistive gas sensors for better amplification. New polymers with long term stability, for the SAW gas sensors.

Non-dispersive infrared (NDIR) is another interesting technique, as it is suited for low cost applications like the ones of food and beverage industry. Measurement of optical absorption is the most widely used optically-based gas detection technique. Microsystems technologies have advanced in the past for the integration of infrared filters and detectors, but there is still room for developing low cost, low power and reliable IR emitters in the range of 3-15 µm. LEDs and laser systems may be good alternatives. Gas cell dimensions of the microdevices are also an issue and new strategies have to be developed.

Figure 3.4 graphically shows the main technological steps foreseen for the two main gas sensor technologies (MOX and NDIR) for achieving the trends and level of integration necessary for real systems in the market with optimum performances for the food and beverage sector.

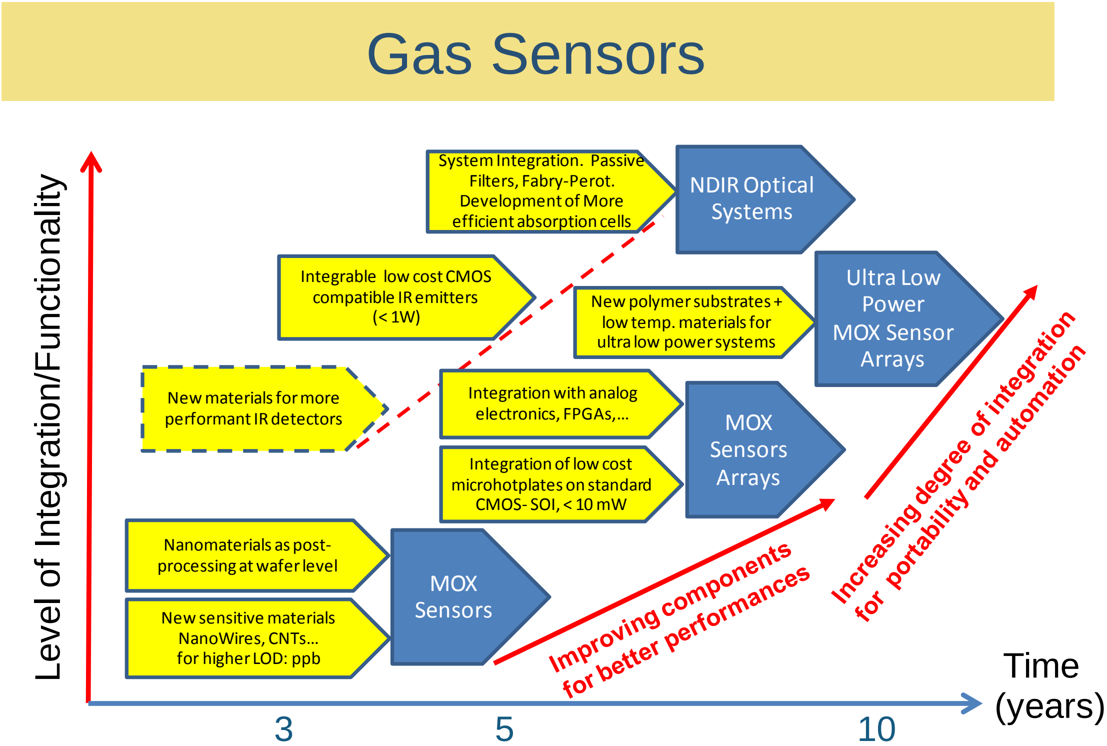


Figure 3.4: Technological trends for gas sensors

e-nose instruments

Instead of using specific sensors for measuring single attributes and quality and safety markets in the food and beverage sector, information can be also obtained from arrays of non-specific sensors with partially overlapping selectivity and treating the data obtained with pattern recognition software. These systems are often referred to as artificial senses. Electronic-noses (e-noses) are interesting examples for volatile detection systems for the food sector. It has to be mentioned that artificial sensing systems have to be tested and calibrated to the target analytes in order to ensure maximum performances. This is known as a training process for the system.

An e-nose is an alternative to single gas sensors for applications for which it is necessary to characterize complex mixtures that are more conveniently identified by an overall fingerprint rather than by the individual identification of their constituents. With appropriate intense statistical training and databases, they can even mathematically tell apart single constituents. They have been widely tested in the last decades mainly for authentication and quality monitoring in cosmetics, food and environmental sectors. In the case of the food and beverage sector authentication and quality of raw materials could be interesting applications for e-noses, mainly for non-quantitative analysis.

Electronic noses are found in many applications in food and beverage. E-noses have been tested in a variety of applications in the food and beverage sector like: classification, detection of aromatic profiles of products for monitoring their processing, discrimination, authentication, determination of attributes of different brands, comparison between beverages of different origins, optimisation of the production process, and several other applications.

Examples for the use of e-noses in the dairy sector are: the classification of milk by trademark and type, determination of the off-flavour in UHT milk, early detection of spoilage bacteria and yeast in milk-based media, intermediate product identification during processing of milk, shelf-life prediction of milk, classification of cheese by ripening stage, detection of mould in cheese…

E-noses in meat have also been studied at R&D level for monitoring the evolution of meat freshness and bacterial spoilage during storage of beef, discrimination of batches of meat, authentication of meat, determination of meat species in processed products, classification of poultry depending of the storage conditions, detection of sex-linked differences, detection of boar taint in pork meat, fermentation of dried products, monitoring of microbiological changes in fresh meat, authentication of pig feeding and ripening time in Iberian hams, etc.

The main advantages of e-noses may be summarised in:

- classification based on sensory analysis
- minimum requirements for trained specialists
- short measurement time
- possibility of portable devices
- potentially automated on-line monitoring of volatiles
- continuous monitoring of food aroma

Electronic noses are not the ultimate answer to all problems. The systems available on the market are generic. For the specific case of food one of the main challenges remain the complexity of the food aromas involved, which requires much better performing systems than the ones available for generic use. This links to some of the problems that can be identified for the currently available e-noses:

- signal drifts
- influence of temperature and humidity
- poor reproducibility
- poor selectivity
- lack of standard calibration procedures
- training based on sensory panel

Electronic noses still show good potential for the food and beverage sector if better and more stable sensor matrixes are used. The improvement of calibration and processing electronics may be also necessary. This could be done by combining the research of food quality specialists and of microsystems developers, as availability of more information on what aspect of the aroma mixtures to be processed with the e-noses are indicative of what properties related to food or beverage quality, would be of great benefit for improving their performances. Thus, the main research trends for the e-nose sensors in the future are:

- improvement of the specifications of the gas sensors arrays based on new more sensitive materials.
- development of different types of gas sensors, resistive, SAW, cantilevers, QMB, electrochemical, optical, that can be combined for the benefit of the improvement of the performances of the sensor matrixes.
- miniaturisation of components for a better integration and reduction of cost, for a better acceptance of the systems.
- improvement of the electronics control systems for a better automation of the systems.
- development of new models based on olfactory human perception for increasing performances and specificity of the systems for food and beverage quality and safety markers.

The main steps of the technological roadmap for the e-noses are graphically summarised in the next figure 3.5.

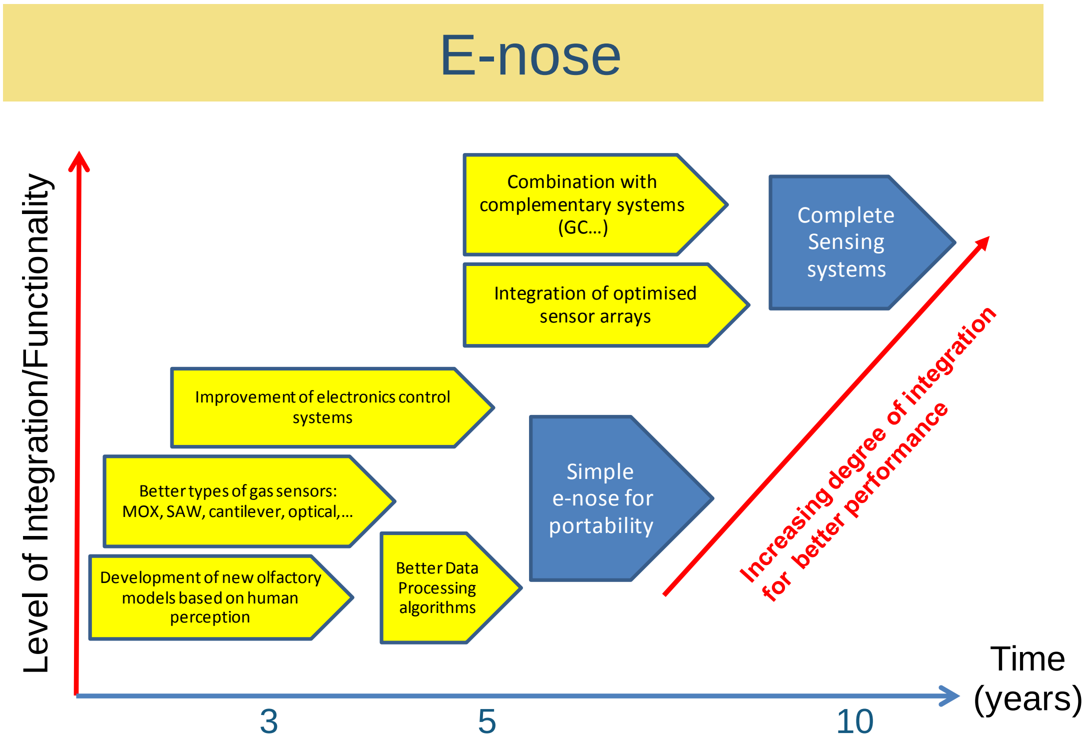
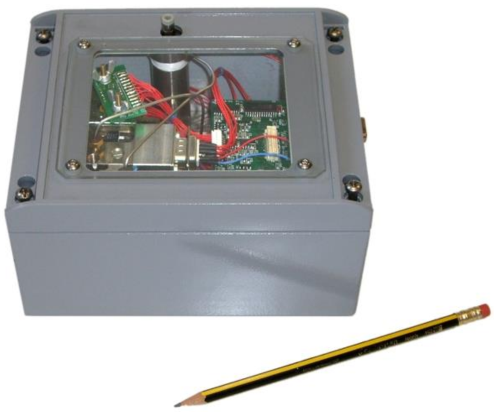


Figure 3.5: Technological trends for e-noses

Micro-chromatographers



Many low cost gas detection sensors have a broadband sensitivity to a range of volatile organic compounds and gases but suffer from poor selectivity. A system approach can improve it if separation elements are used prior to reaching the sensing devices. Gas Chromatography (GC) is considered one of the most reliable separation methods. But GC systems are very expensive and laboratory based. Research on the application of microsystem technologies to down-size GC systems has been done in the last decade but because of the small dimensions they still show poor performance. However, as micro GC is being studied for other applications. The food and beverage industry may benefit of such developments.

As for the other systems already presented, to comply with food and beverage requirements, it will be necessary to improve micro GC performances:

- More sensitivity: Increase dimensions of micro-columns, improved stationary phases
- Filtration and pre-concentration
- Better detector matrixes.
- Miniaturisation of the systems.
- Increasing the integration for lowering cost of systems.

Figure 3.6 shows the technological steps of the roadmap identified for the new generation of gas micro-chromatographers.

Micro-Chromatographers

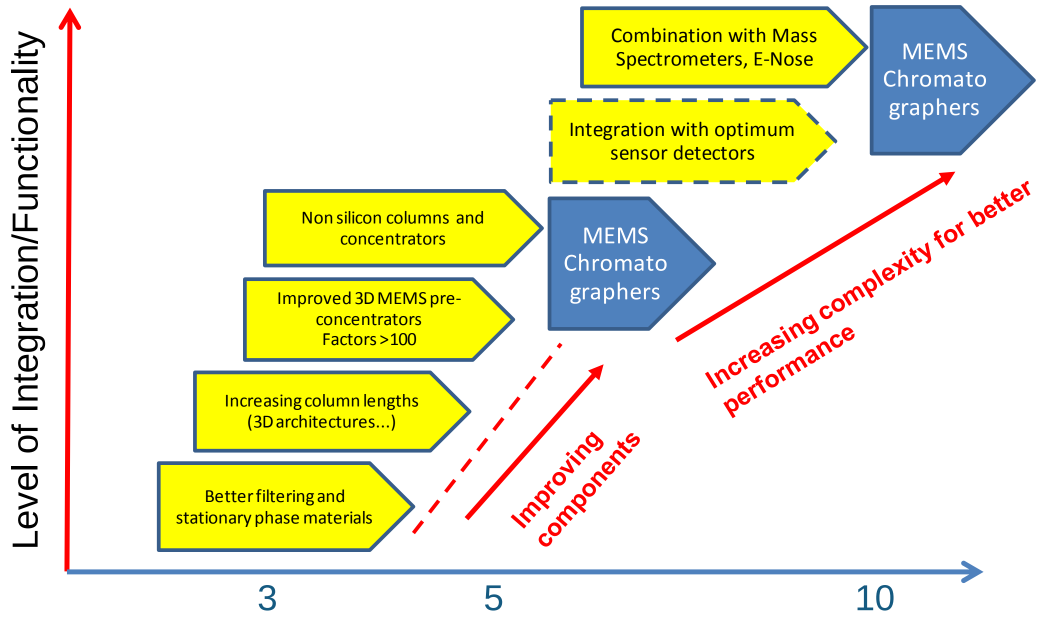
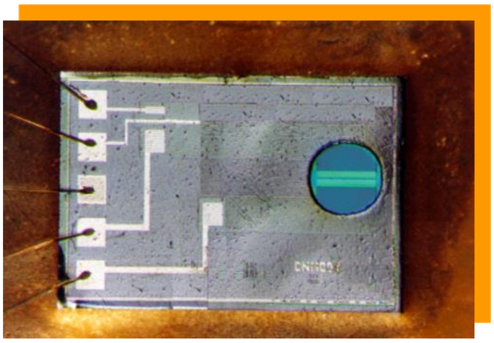


Figure 3.6: Technological trends for micro-chromatographers

3.1.2 Biochemical Sensors



In food and beverage a noticeable amount of quality attributes and safety problems cannot be related to an aroma but to the taste or to a marker that has to be measured in liquid media. In this case, chemical and biochemical devices and systems are the most appropriate.

Possible applications in the beverage sector are: identification of the aromatic richness of grapes and materials (e.g. barrels), authentication, classification, polyphenols contents, dissolved gases in beverages, pesticides, pH, redox potential, detergents and ions in water, etc.
For dairy and meat, many analytical requirements for safety assessment may be based on biosensors. Tetracyclines, aflatoxins and other mycotoxins pathogens are examples of concerns of the food producers.

Biosensors and chemical sensors only differ with respect to the biorecognition layer, which is crucial for the biosensors. In fact, most of the recent and probably future advances in biosensing systems are more related to the performances of the biolayer than to the transducer itself. Biosensor development is a multidisciplinary activity combining biotechnology know-how with microsystems and microelectronics technologies and chemometrics.

A great variety of devices and technologies have been developed that can be of use in the food sector. In figure 3.8 the main technologies for the chemical transducers and for the biolayers are summarised.

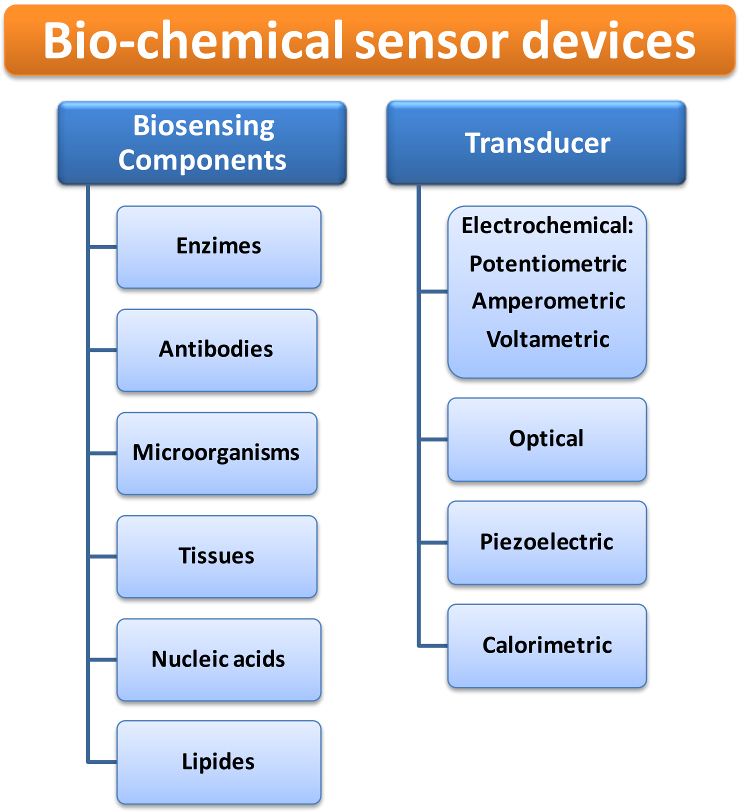


Figure 3.8: Summary of main microtechnologies and materials for bio-chemical sensors

Among chemical sensors for detecting substances in food and beverage, the electrochemical (also classified as potentiometric, amperometry, voltammetry and conductimetric sensors) are the most widely developed. An electrochemical sensor is defined as a chemical sensor that responds to specific changes on its potential or current as a consequence of the presence of a chemical substance that interacts with it. Generically they are known as Ion Selective Electrodes (ISE). The sensing material in contact with the solution may be organic or inorganic and when it is a biomaterial, then we speak about biosensors.

Thanks to the biological part and its associated specificity, biosensors are able to measure the concentration of a single component, even in a complex mixture. Thus, biosensors can be good alternative methods to some of the complex laboratory analyses. Biosensors have been very popular at the research level in many applied fields, due to their performance in terms of measurement time, sensitivity, and potential low cost. In fact, biosensors for healthcare (e.g. glucose monitoring in diabetes patients), and environmental monitoring (e.g. the detection of toxic substances in water) have shown their potentialities also at industrial level.

A biosensor is different from a bioanalytical system, which requires additional processing steps, such as reagent addition. Furthermore, a biosensor should be distinguished from a bioprobe which is disposable after one measurement.

To increase the selectivity of biosensors, different types of chemical and biological elements can be used (enzymes, antibodies, nucleic acids, cells, tissues, microorganisms…). Enzymatic biosensors are the most promising for the food and beverage applications (food safety and quality control and the determination of residues, among others). The enzyme layer defines the biosensor selectivity and by substituting it the sensing capability changes, which gives a lot of flexibility and potentialities to the biosensors use.

The main advantages of biosensors compared to the traditional laboratory methods are:

- they allow detecting an analyte without purification of the sample;
- they can be highly specific (i.e. enzymatic), or with a degree of unspecificity (microbial);
- fast measurement able to be integrated in portable systems;
- the systems based on biosensors use low volumes of sample and low amounts of reagents, reducing costs;
- the specificity of the biological recognition makes it easy to operate biosensors in complex food and beverage matrixes;
- relatively easy data processing.

On the other hand, some drawbacks have to be taken into account in order to define the potential for the future:

- the global performances are more associated to the material than to the transducer. Further research on novel materials is necessary
- depending on sampling and on the application, biosensors may require the development of a low cost disposable part attached to the transducer
- it is possible that biosensors require the combination with Flow Injection Analysis (FIA) systems and electronic signal conditioning circuits because of the usual drifts associated to the baseline electrical measurement of single bio-sensing devices
- it is necessary to optimise not only the transducer but also the associated electrochemical cell, as part of the improvement of the whole sampling method.

Thus, the main trends on R&D associated to the biochemical sensor development for the food and beverage can be summarised as follows:

- to introduce new material that ease the chemical and biological recognition
- to develop and use new methods of immobilisation of the biomaterials on the surface of the transducer: new membranes, gels, magnetic particles etc, for improving the sensitivity, stability and life-time
- to develop simple label-free systems

- to achieve a sufficient degree of miniaturisation that gives at the same time good performances and low cost. To develop systems that combine single use cartridges and highly performing reading systems
- to develop portable microsystems, with low power electronics and wireless communication for in-situ monitoring of food and beverage products during its production and life-time.

Figure 3.9 graphically summarises these trends for bio and chemical sensing devices.

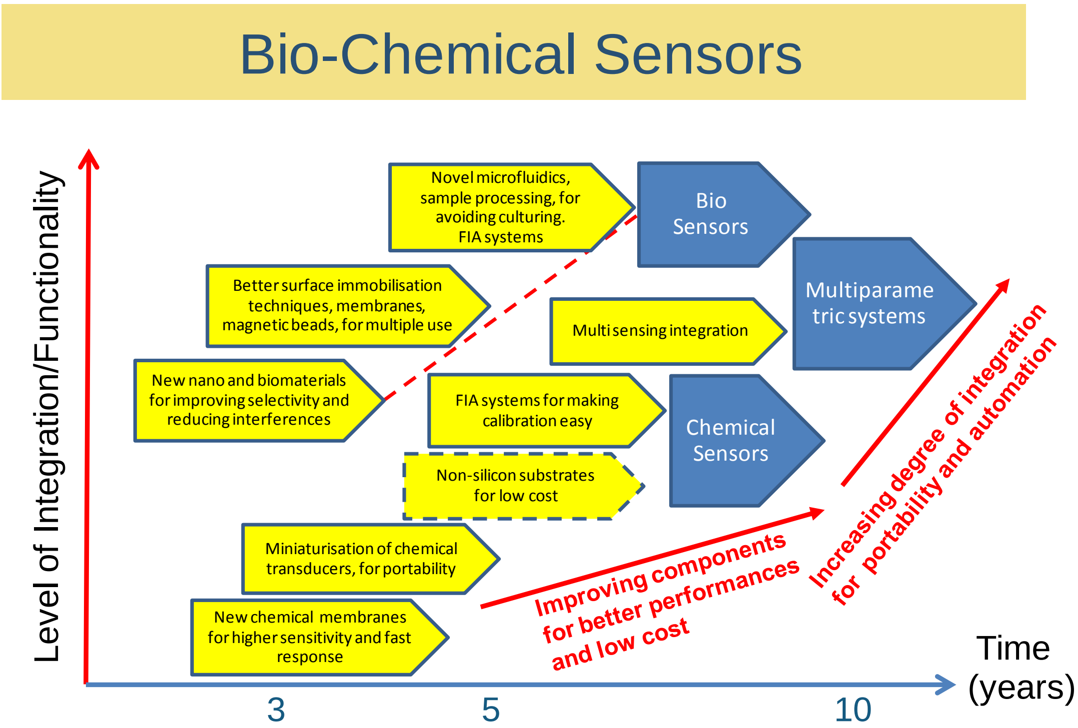
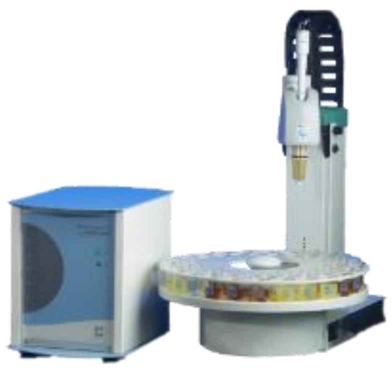


Figure 3.9: Technological trends for bio-chemical sensors.

e-tongue systems



Concepts similar to e-nose, but for use in liquid media, have recently also been developed for the food and beverage sector. These systems are related to the sense of taste in the same way that the electronic nose relates to olfaction and are usually known as taste sensors or electronic tongues. The study of taste sensors is still at an early stage. An electronic tongue is defined as a multisensory system, which consists of a number of low-selective chemical or biological sensors and a signal processing module based on pattern recognition and/or multivariate analysis. With it, both qualitative and quantitative (in some cases) determination of the attributes and markers of food and beverages can be performed in a simpler way compared to traditional laboratory analysis.

In some applications, there are advantages when measuring in liquids compared to measurements in gas, as many compounds such as ions or those having a low vapour pressure can only be measured in liquid phase.

The performances of an e-tongue can be considerably enhanced by the combination of sensors based on different technologies, electrochemical being the most important ones. Potentiometry and more recently voltammetry are the most used among the developments already done, when the sample is charged. Otherwise, other techniques (such as optical, gravimetric) should be evaluated.

The main applications of e-tongues in food and beverage, for the special cases of the sector covered in this study are:

- For the beverage sector: evaluation of raw materials and evolution of taste and flavour of beverages at the different stages of their production, taste objectivation, classification and discrimination of beverages, authentication, detection of alcohol contents, quantify bitterness in beers, differentiate varieties and food and beverage (including mineral water) brands, determining flavours of commercially available fruit juices and soda drinks, etc.
- For the dairy sector: discriminate fresh from spoiled milk, analyse flavour ageing in flavoured milk,…
- In the meat sector, some R&D studies have been done for the determination of salts, nitrates and nitrites in minced and processed meat and sausages.
- For environmental issues: monitor agriculture and industrial pollution of air and water, monitor environment with respect to water, metal ions, endotoxins, pesticides.

As seen, e-tongues bring some advantages that make them very suitable for analysis in the food and beverage sector compared to single chemical sensors:

- single sensors usually cannot cover all analytes and sometimes are not sufficiently selective, while multi-sensors on the e-tongue can cover all and are selective.
- if e-tongues are miniaturised compared to laboratory systems, less chemicals are needed, and less waste is produced. Also less sample volumes are needed.
- if properly trained, e-tongues can give quantitative information of the analyte under test even within complex matrixes.
- e-tongues can also be combined with miniaturised flow-through systems that may help on the calibration of the systems, and give short response time
- e-tongues may benefit from the combination of many different types of sensors, specific and non-specific to obtain maximum information from the samples.

On the other hand, some drawbacks are not yet fully solved:

- e-tongues, as e-noses, are sensitive to environmental factors: temperature, humidity (for e-noses), sensor poisoning, that produce background noise to the measured signals obtained from the sensors. This makes it difficult to measure very low concentrations of the analytes.
- the performance of the systems, largely depend more on the chemical, biological layer and on the signal amplification and data processing than on the Microsystems transducer itself.
- in some cases, the improvement of the specifications implies developing more complex systems (i.e. combination with e-noses)
- low cost is not easily achieved for complex e-tongue systems.

In summary, some R&D trends may be identified for the e-tongues that are in two directions: first the improvement of the materials (nano and or biomaterials) and technologies of the sensor arrays for the miniaturisation of systems for easy on-site use and second, the improvement of the specifications by making more complex and complete systems and integrating different subsystems for bench-top instruments that could complement traditional measurements in the laboratory. In all cases, it will be necessary to improve pattern recognition tools, to process higher amounts of data and to increase the knowledge of users on specific applications, if e-noses have to be well trained. In figure 3.10, these trends for the future are graphically shown.

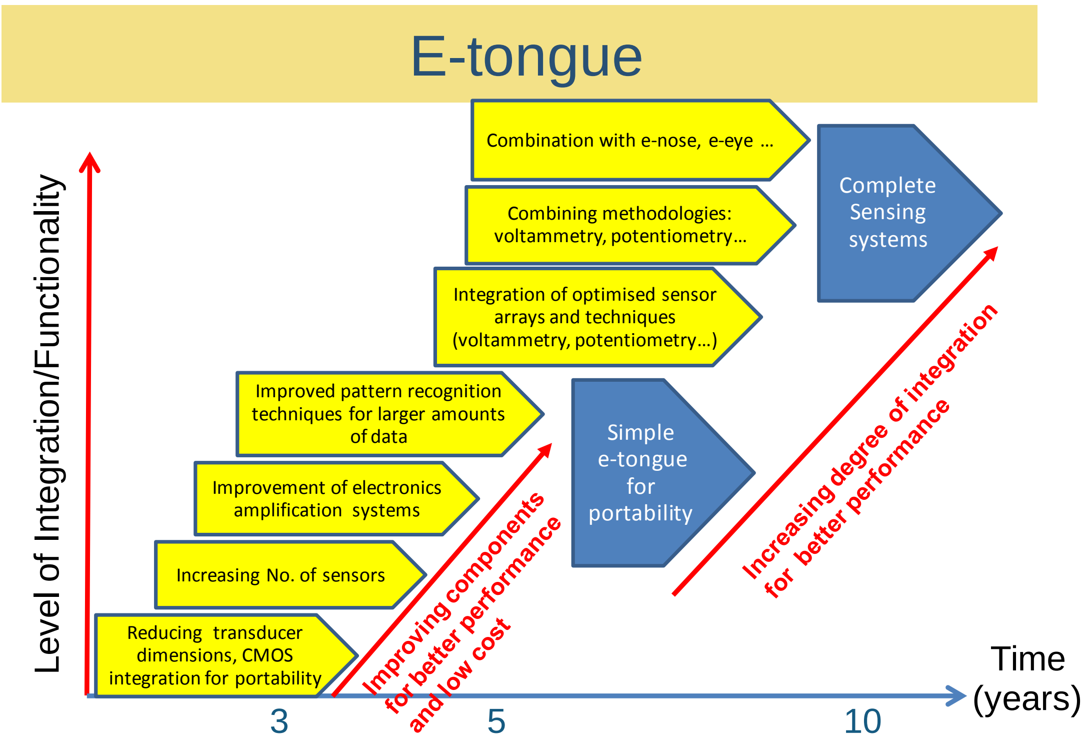


Figure 3.10. Technological trends for e-tongues

4 Microorganism detection

There is a growing need for biosensors in food industry (along the whole food chain) in microbial food safety as well as by legal/governmental inspection agencies. The biosensor market is rapidly expanding with estimates of a growth from €5,100 million in 2009 €11,000 million in 2016 (*source: Frost & Sullivan, June 2010, Analytical Review of World Biosensors Market).* These data include biosensors dedicated to chemical contamination. Specific numbers of turnovers of biosensors aimed at microorganism detection either in terms of money or number of units are not available. According to the same source the price sensitivity, the degree of competition as well as the need for technological innovation is extremely high.

The main areas for applications of biosensors include product safety (detection of pathogenic microorganisms in food and food contact material) and product quality (detection of commercial microorganisms, e.g. starter cultures in dairy products). The main motivations for their utilisation include:

- Increasing automation of food production including increasing time efficiency due to in-, on- or at-line control.
- Presence of standards/ food laws and regulation which addresses increasingly more topics following continuous decrease of LOD and LOQ (limit of detection / quantification). In addition food industry has much more regulations with respect to microorganisms than any other industry.
- Changes in the demands of consumers require new methods to check differentiated streams of raw materials, e.g. organic food can contain much more pathogens (e.g. Salmonella in eggs or *S. aureus* in milk).
- In the spirit of sustainability and demand for less processed foods by consumers it can be anticipated that new processing technologies – with less energy consumption – will be implemented in food industry. These technologies, e.g. some new pasteurisation strategies, might lead to an increase of pathogens.
- Increasing consumer concern with regard to food safety due to food scandals were microorganism caused serious health problems.

The main added value for use by the food and drink industry includes:

- Time: the detection of microorganism at-, in-, or on-line in a very short time frame replaces time consuming microbiological reference analyses (off-line methods e.g. plate count agar techniques with specification in a second step) or very expensive methods, which might be commercially available (e.g. real time PCR).
- Price: whether an automated system or a dip stick approach can be used, these fast detection approaches may become very cheap once mass produced.
- Handling: most likely fast detection of microorganisms (e.g. dip stick technique) is easier to perform compared to many current methods. This means that employees without special training and education can perform these analyses on a regular basis – there is no need for highly qualified lab personnel to be available at all times.

- Food Safety & quality: In the case of an "abnormality" a quick answer, whether a specific food or food production line is contaminated can ensure food quality, can protect against unnecessary food recalls and – in a worst case scenario – could save lives (e.g. EHEC 2011, Germany)

A major constraint is the cost: the process of developing a new biosensor is very expensive. The main reasons are that requirements of selectivity, reproducibility, reliability or robustness are not easy to develop.

4.1 State of the art

So far researchers have not been successful at producing biosensors that meet the high expectations of the food industry (*source: Frost & Sullivan, June 2010, Analytical Review of WorldBiosensors Market)*

Fast detection methods are not accepted by the regulatory authorities. Regulations define specific reference methods that *have* to be applied for food law issues. This means that novel, fast detection methods cannot be used to replace current methods before they are defined as an accepted reference method. In practice this implies that new methods have to prove their quality for many years before they even have the chance to be considered as a reference method. Even then it will be quite complicated to replace the reference method of commercial and/or governmental labs, since this includes a high administrative amount of work for each country, and in addition to harmonize the new method at least on the EU level, preferable on a global level. Although the fast detection methods are not allowed by regulatory authorities, they can be used for screening of products and materials to reduce the number of expensive tests.

Various possibilities exist to detect microbial contaminations that follow different strategies and have different target molecules. This results in specific techniques for specific questions and applications. The following table provides examples for nowadays MO detection:

Technique	Target molecule	Advantage	Disadvantage	Duration
Differential Microbiology	Life MO	Exact quantifiable	Highly trained personnel Full laboratory Only life MO	> 5d
ELISA (including Dipsticks and lab based approaches)	Proteins	Exact May be developed as dipstick test	No automatisation, Long, costly development for each assay	Minutes to 1 day
HPLC-MS/MS	Proteins/ Peptides	Exact quantifiable	Highly trained personnel	2 days
Gas sensor	Volatile Molecules	Fast *In-line*-integrateable	Unspecific	minutes
PCR	DNA	Exact, quantifiable	Highly trained personnel, expensive	2 days
RT-PCR	RNA	Exact, quantifiable Dead/life	Highly trained personnel	2-3 days

Table 4.1 Overview of current methods for microorganism detection

4.2 Description of a new device and technological needs

Techniques mentioned in table 1 have specific disadvantages – whether, it is time or cost or others. Therefore, as already proposed in the dairy roadmap, a new approach is consequently required for the detection of microorganism in an at- or on-line mode. The following idea – a µPCR – fulfils the needs of industry in terms of regulations, speed, price and robustness, keeping the specific detection of pathogens in mind.

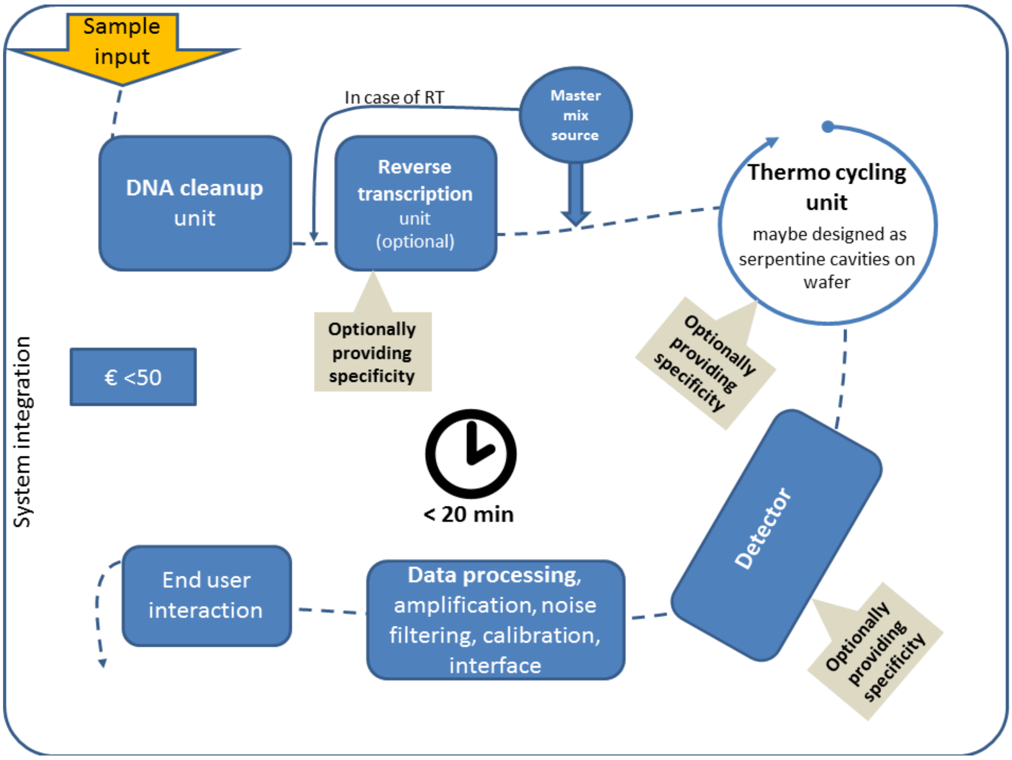


Figure 4-1: functionality of a "µPCR" device

The figure 4.1 provides a schematic representation of the functionality of a "µPCR" device for miniaturised detection of food pathogens based on genetic material, either DNA or, more sophisticated RNA. The latter approach would allow to distinguish whether a detected organism is still alive or not since RNA is readily degraded in an ex vivo environment or in a dead organism. However, this would effort an extra step in which RNA is reversely transcribed into DNA. In the future, modern polymerases will allow a decrease of required time dramatically, allowing for cycling intervals of a few seconds.

Independent of the technology to be developed – the food sector is very price sensitive. This results in small profit margins. Price elasticity in foods is general large, meaning that consumers will easily switch to alternatives if increasing price does not deliver substantial benefits to them. As a consequence additional cost in a production chain can hardly be recovered from increasing profit margin (which is very small to start with) or by generating additional consumer spending (which is unlikely to happen). In addition, consumers expect food to be safe, fresh and healthy; deviations from the best possible level of these attributes will be seen as a deficiency in the food (a dissatisfier) while investments to further improve these will not be considered to add value to the product from the point of view of consumers. Food producers therefore will not accept new technologies along the food chain that increase the price, even if somewhat better quality and control can be offered. For niche or high-price segments there are more possibilities as these segments aim at added quality above the base line expectancy, and margins are somewhat larger.

Hence the best chance for microtechnology in the food chain is by creating applications whose costs can be fully recovered by increased cost-efficiency within the chain. Lower product losses would for example create revenue within the chain that may warrant additional tests.

The use of microsystems can potentially reach the required low prices per test with a higher level of integration. For this, independent of the technology used, the following steps need to be considered:

- Reduction of material costs per test, e.g. substitution of expensive materials
- Reduction of size
- Reduction of process costs, e.g. substitution of clean room processes by less time- and cost-consuming process steps (e.g. roll-to-roll fabrication, use of polymers instead of Si-based technologies)

The Figure 4-2 visualizes the implementation of these steps using the example of microorganism detection by µPCR. In a first step the conditions for future developments must be paved. This will require an independent development of device units that will for example allow for easier sampling, faster evaluation and a reduction of fabrication costs. Another topic could be the optimization of the required polymerases, master mixes (containing all reagents and chemicals for reaction) and protocols.
The next major advancement would be to engineer a mobile device that could be installed into a process line and somehow run and evaluate the analysis without the need of trained personnel.
The goal should be a device in hand-held size (comparable to a mobile phone) which is competitive to laboratory methods in terms of costs and reliability. These devices could be carried permanently from the technical staff of the e.g. dairy plant to analyse spontaneously or according to a test-agenda. Moreover these devices should become integral parts of the process lines in order to permanently monitor the product quality and automatically alert in case of deviations from the desired specification.

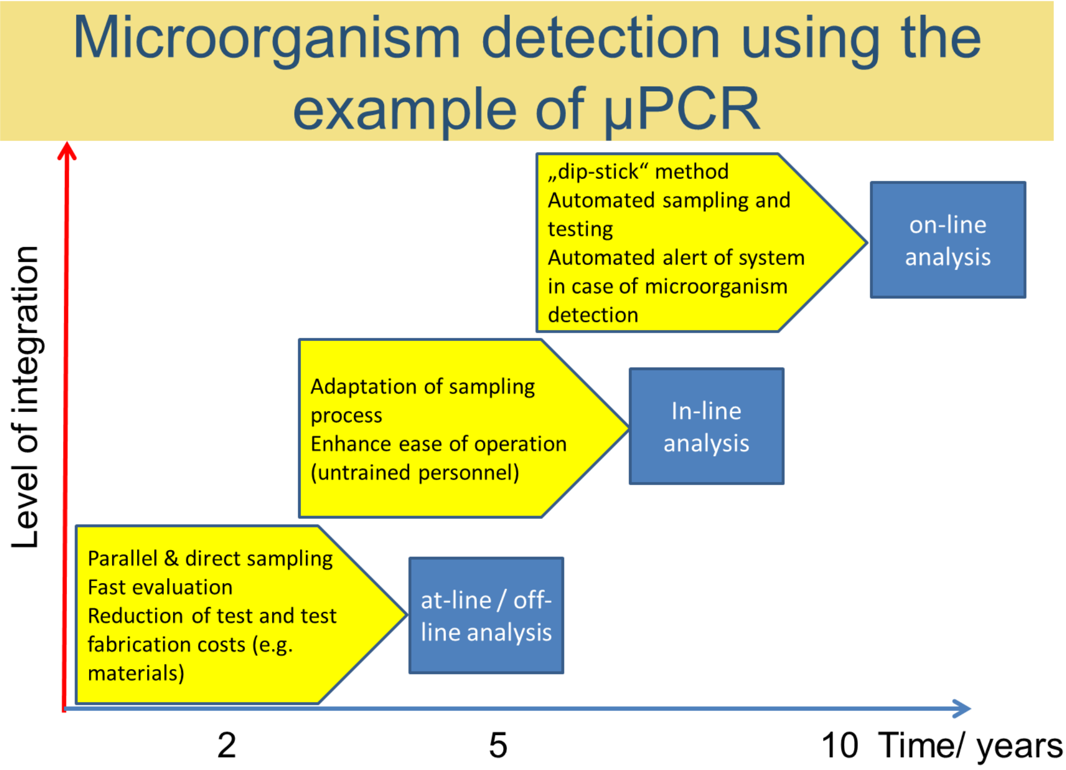


Fig. 4-2: Microorganism detection using the example of µPCR.

The higher levels of integration will be reached using the technology developments given in the yellow arrows.

5 Tracking and tracing systems

Food traceability is part of logistics management that captures, stores, and transmits adequate information about a food product at all stages in the food supply chain so that the product can be checked for safety and quality control, traced upward, and tracked downward at any time required. Tracking and tracing also helps to determine the correct origin of food products.The figure 5-1 gives a schematic representation of the “tracking and tracing” concept (Bosona, 2013)[2].

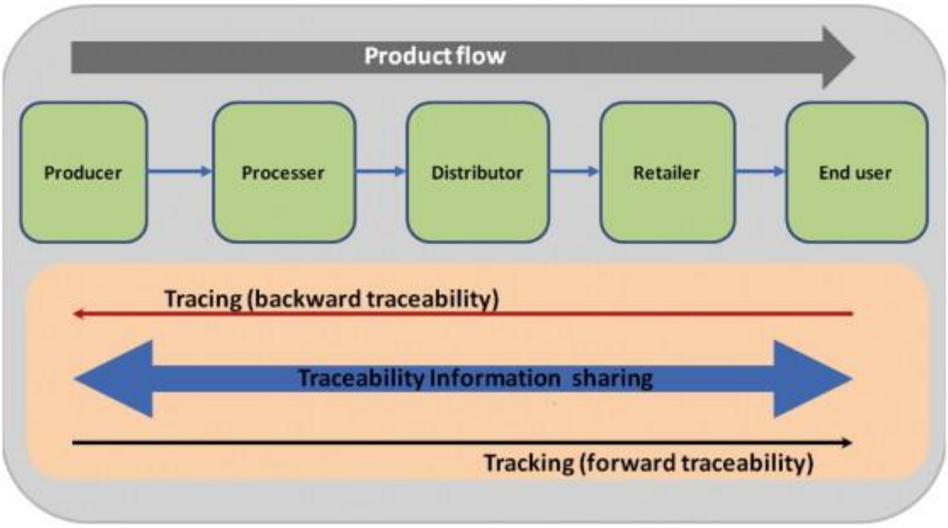


Fig.5-1 Conceptual representation of material and traceability information flow that best reflects the case of food supply chain [Bosona, 2013].

[2] [Bosona, 2013] T. Bosona and G. Grebensenbet, “Food traceability as an integral part of logistics management in food and agricultural supply chain” Food Control 33 (2013) pp.32-48

When there is a need to collect information at various stages of food production or to measure specific parameters electronically, microsystems technologies (MST) are often involved in the first steps of the authentication and tracking & tracing systems. Companies can also use tracking and tracing tools to analyse key data at each step of manufacturing process: for food and beverage products. Maintaining consistency across facilities and batches requires having enough correlated data that can be analysed to identify needed improvement in operations. Thanks to low cost integrated sensors embedded in (i) identification tags (on live cattle, food raw materials, packaging of the final products...), (ii) in-line process equipment, (iii) handheld scanners, (iv) transport boxes, manufacturers and retailers will continuously gather measured data about their production yield and reliability., For instance a food producer might know if the final quality is impacted by the use of a specific equipment or by external factors such as water supply or by the weather.

There are some differences in food traceability requirement and constraints among the main food sectors. For instance:

- The dairy industry is characterised by complicated stock management. Cheese ripening for example requires a correct insight into the ripening process. During order entry, the sales assistant should know what cheese sorts are in stock and when these will be available. Finished products are placed without a label in stock and then provided with a private label based on the order date. A correct insight in the ripening process, whilst maintaining tracing data, can save the manufacturer a lot of time.
- The dairy and the meat sectors share the same need toward animal identification. It is vital that farm animals and products are traceable backward and can be tracked forward from the farm level, through intermediary steps, to the next level of the agri-food chain. All intermediary steps, such as trucking, assembly points, sales barns, and feedlots are concerned.
- The meat industry is characterised as a branch that must meet strict legislation such as HACCP[3], tracking and tracing, labelling, etc. Other important issues are cost price calculations, stock management and

[3] Hazard Analysis and Critical Control Points

responding to customer specific requirements as regards packaging, processing and labelling.
- For the sliced and fresh meat sector and for other fresh products such as fruits and vegetables or raw milk, the margins are narrow and the turnaround time between order entry and delivery is very short. To match these needs the technology must provide very efficient solution (e.g. the cost of tags should not be higher than the price of ink labels, from a few cents down to one cent) and software solution providers must also solve the big files processing problems at moderate cost because the MST offer will not develop without the implementation of efficient solution at the retail stage.
- The wine industry is becoming increasingly aware of the growing counterfeit threat for high-value products. The most common methods of counterfeiting involve the reuse of genuine packaging, with refilling or relabeling common practice. Securing bottles with methods such as laser engraving fails to provide significant protection against counterfeiters as these can be re-filled and it also potentially makes it easier to sell as such bottles can successfully go through an authentication test. Authentication of the cork is also not a favoured option because government regulatory bodies often do not allow any sort of foreign material to be used on it as it comes in contact with the wine and could potentially affect its quality.

Regulations regarding food traceability require tracking and tracing. This can be the stimulus for more transparency within a company.

The main benefits of a traceability system for food supply chain management (FSCM) are:

- Increase in consumers' satisfaction
    - Increasing consumers' confidence in food and reducing customers complaints (increased food quality and safety)
    - Promote easy food choice e.g. for consumers with food allergies
- Improvement in food crises management
    - Improving crises management in event of hazard incidence. Enabling authorities to identify hazardous foodstuffs (and withdraw from market) and detect fraud
    - Tracing the origin of foodstuffs and ingredients
    - Controlling animal and food related diseases
    - Reducing counterfeiting, liability claim, and lawsuits
    - Reduction of out of date/spoilage cost
    - Reduction in the volume, cost, frequency, and severity of product recalls as a result of increased capacity of detecting the vulnerability at early stage
    - Reduction of media impact on the food companies by facilitating food recall action
- Competence development. Improving competitiveness of the food chain members (traceability has promotional capacity)

    - Increase access to contracts and markets
    - Protecting brand name and reputation of firms
    - Increasing labour productivity
- Technological and Scientific contribution
    - Enabling availability of scientific data for effective research to identify the cause of food hazard incidences
    - Promotion of new technology such as IT advancement
- Contribution to agricultural sustainability
    - It strengthens the implementation of sustainability initiatives in food production, handling and distribution as the traceability data could be used for assuring ensuring that food is sourced from appropriate sources or farms

RFID solutions induced a lot of excitement in the 2000s. The retailer Walmart had announced the most ambitious project, requiring its top 100 suppliers to equip all their pallets with RFID tags by 2005 to enable ICT supported tracking and tracing. But cost overruns and implementation glitches led to cancel the initiative. In 2013, new large scale experiments are on the track e.g. the Japanese governmental system for authentication of their national beef production since 2010 or the French retailer Auchan since 2011 (please refer to D4.3 report). These more recent initiatives take due account of the cost issue: cheap bar code in Japan served by a restraining regulation (please refer to D4.3 report) and re-usable RFID tags read by fully automatic portal systems were applied by the French retailer. Many other examples of traceability system within the food supply chain are driven by large retailers and located in the US. It is worth mentioning some of them since they provide interesting insights to drive the future development of efficient traceability systems in the EU:

HarvestMark & Kroger company

HarvestMark created a bar code that allows the consumer to scan the 16-digit code with a cell phone camera and, using an iPhone app or the company website, follow the trail of the product from farm to processing to shipping to store. The Kroger Company operates in more than 2,400 stores in 21 states of the USA.

Frequentz' track-and-trace solution integrated with IBM's InfoSphere Traceability Server (ITS) acquired by Frequentz in 2012 is a combined solution based on Information Repository & Intelligence Server (IRIS).

Freshtime™- RFID EPC and NFC hardware and software - Answering, "Is it fresh?"

A perishable integrity indicator[4] system includes

- an RFID transponder (RF integrated circuit coupled with an antenna)
- a perishable integrity sensor monitoring the time/temperature[5]

4 Infratab Bangalore Pvt Ltd, 2012 http://infratab.in/

5 US4057029 "Time-temperature indicator" (1977)

- a freshness determining module[6] that receives time/temperature dependent measurement data and determines status.
- a communications interface to the RFID transponder (Bluetooth, Zigbee,…)
- an RFID reader to retrieve current freshness status data
- a power management module
- a visual and audio communication interface provides a communication means for sending sensor alerts, sensor setup and history as either a supplement to the RF communication or as an alternative to RF when RF is either not available or not able to communicate[7].

Rehrig Pacific Co., and Intelleflex and ZEST Data Services formed a partnership to improve traceability of temperature-sensitive products in the cold supply chain thanks to intelligent reusable transport packaging solutions

- on-demand data visibility for tracking and monitoring the temperature and condition of temperature-sensitive products, such as fresh, frozen and packaged foods.
- Using ZEST Data Services, personnel are alerted to real-time changes in temperature and other environmental factors that can impact the integrity of the shipment and potentially expose customers and an organization to significant risks relating to quality and safety.

In the EU, the FP7 project PASTEUR developed a smart sensor tag to manage the fresh product chain. The tag shows where the product comes from, under what conditions it was transported and the product's actual shelf life: the temperature and gas conditions registered during transport and storage is used to estimate a dynamic shelf life. http://www.pasteur-project.info

The main barriers to the implementation of tracking and tracing systems include:

Costs: the cost of tags is a barrier for the food industry, which operates on very narrow margins. Putting a bar code on a pallet might cost the distributor a fraction of a penny versus the 7 or 8 cents of an RFID tag. RFID tags work faster and can be read at a longer distance than bar codes. Price of RFID isn't likely to change since material an production costs are still too high. Current RFID tags will only be interesting for large scale application to food if there are changes in what you can do with the tag and these new additional capabilities is where a business case can be made for RFID technology in food production.

Standards: The globalisation of food, and the intricate connections between food producers requires general standards. RFID companies must co-operate or be mandated by governments to cooperatively develop interoperable systems. The first step is the establishment of worldwide standards similar to the ISO standard ISO11784 and ISO11785on RFID of animals. Experts agree that the RFID industry has a long way to go to ensure that all RFID tags and readers can communicate and that

6 US20050248455 "Shelf-life monitoring sensor-transponder system" Claim 1: (…) characterized by transferring the freshness status data to a second perishable integrity indicator system."
7 US20070273507 "Apparatus and method for monitoring and communicating data"

the data can be exported easily to any of the commonly used company management systems. Standard limitation includes:

- Lack of uniformity in implementing the traceability systems i.e. different companies use different standards information exchange.
- Different links in the chain have different level of accuracy of traceability.
- Lack of integration and transparency in retrieving traceability information along the whole food chain.
- Data related issues such as data protection, trust, privacy/security, and reliability, including concerns about post purchase tracking of consumers.
- Problem of information asymmetry along supply chain.

5.1 Description of the devices and technological needs

The figure 5-2 illustrates the priority issued by the food industry, the capabilities needed to answer these priorities and the type of devices needed. The diagram was built from the meat sectors since it appeared from preliminary investigation that the high diversity of this sector leads to a good overview of all the relevant aspects.

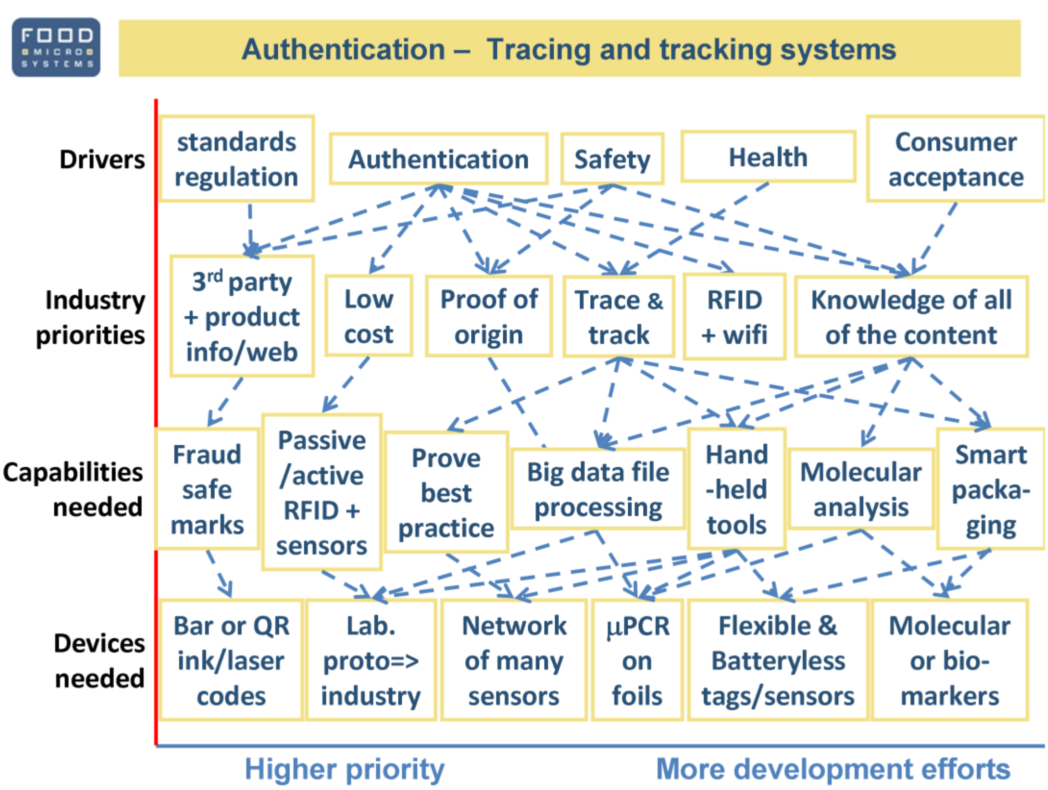


Fig. 5-2 Industry priorities, capabilities and device needed for tracking and tracing systems

The consumer demand somewhat matches the regulation requests while the needs at the retail stage are highly constrained by cost issues. However the consumer acceptance toward an extra cost can be increased thanks to additional new benefit (e.g. food safety insurance.

The three key objectives that have been highlighted are listed below. They have led to the roadmap “tracking and tracing” described in this main section:

1. A techno-push pathway where technology providers will look for increased performance at reduced cost. It is highly desirable to push already existing laboratory demonstrators into mature products (e.g. handheld scanners specifically developed for given measurements for the meat sector or transponders that can do the measurements in individual animals) and help them enter the market by addressing also demands from other industrial sectors. Simple architecture that does not need battery powering or that makes use of biomarkers instead of exogenous markers would surely reduce the production costs, but research effort is still required to gain performance.

2. A market-pull pathway from which retailers will get relevant information allowing them to improve the control on the logistic systems via direct information on the quality and/or ripeness of food products. Microsystems might then bring key technologies to increase the effort for not only safer food but also better taste and texture.

3. The consumer demand for environmental sustainability, the food producers looking for low cost solution and the regulation, the three of them offer a common development pathway for microdevices batch processed on thin, transparent and flexible substrates. These substrates are much cheaper than silicon-based technologies. In a longer term fully recyclable solution should be targeted.

Technological roadmaps

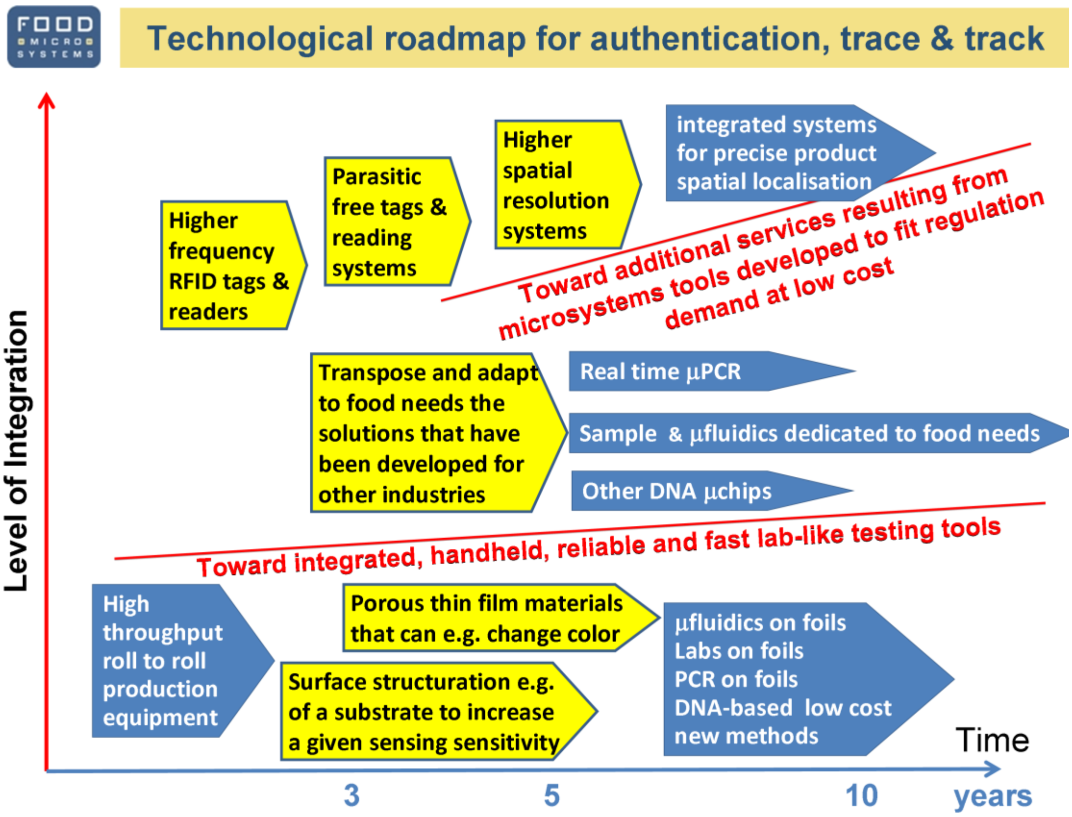


Fig.5-6 Technological evolution recommended to fit food sector needs

The microsystems that fit the needs of the food traceability systems face on the one hand a technology challenge to achieve low cost and thus passive and battery-free RFID tags including embedded sensors with their associated first electronic stages and fulfil the environmental concerns for mass use of smart packages and on the other hand a challenge to manage the massive data flows that are requested to safely guaranty the origins of ingredients in all kind of food products and prevent or better control food crises.

The technologies either applied or envisaged for product traceability purposes include:

- For identification
    - Bar codes. Manufacturer identification number, item number, packed date, batch number – Widely used for inventory control, stock recording and checkouts
    - Tag (e.g. RFID tags) that should withstand tear, wear, and harsh environmental conditions. They can also be used as time-temperature indicators or EID[8].

[8] The tag carries a unique label (a 10 to up to 32-digit number) that is read either directly or using an optical reader (barcode) or using a RF based contactless reader (RFID) or using other kind of scanners (electronic tags)

- For quality and safety measurement
  - Penetrometer, firmometer, twist tester, Instro machine, Kiwifirm – Firmness of fleshy products (to measure quality and safety status)
  - Infrared & magnetic resonance imaging – Firmness of product, presence of hazardous physical objects inside food products
  - Equipment for chemical analysis – Presence of hazardous microbial contaminants
  - Smart packaging devices (e.g. pH indicators, chemical bar codes) – Growth of bacteria (e.g. for real-time monitoring of fish spoilage)
  - Nanotechnology based devices (Nano sensors) – Presence of pathogens, gases, spoilage, changing temperature and moisture, chemicals, and toxins. They can be applied as Nano sensors in smart packaging and as portable Nano sensors

- For genetic analysis
  - DNA tests to for the authentication of products, for pathogen detection or to test quantity of GMOs and other transgenic materials

- For the monitoring of storage condition
  - Intelligent packaging (temperature-indicator, freshness-indicator, Gas-indicator, biosensors) – Temperature, relative humidity, atmospheric composition of the air (including pollutant). To analyse impact of external environment on quality and safety of food

- For geospatial data capturing
  - GIS, RS, GPS Site specific data on animals and their movement, plants on the farm – To remotely collect and integrate data, and map geospatial variability
  - Nuclear techniques Isotopic and elemental fingerprints – To determine the provenance of food; to identify the geographical origin and source of contamination

- For data exchange
  - EDI, EXL Exchange of standardized and structured data To facilitate information sharing particularly via internet Software
  - QualTrace, EQM, Food Trak Integration of technologies for full traceability system Example of commercial software

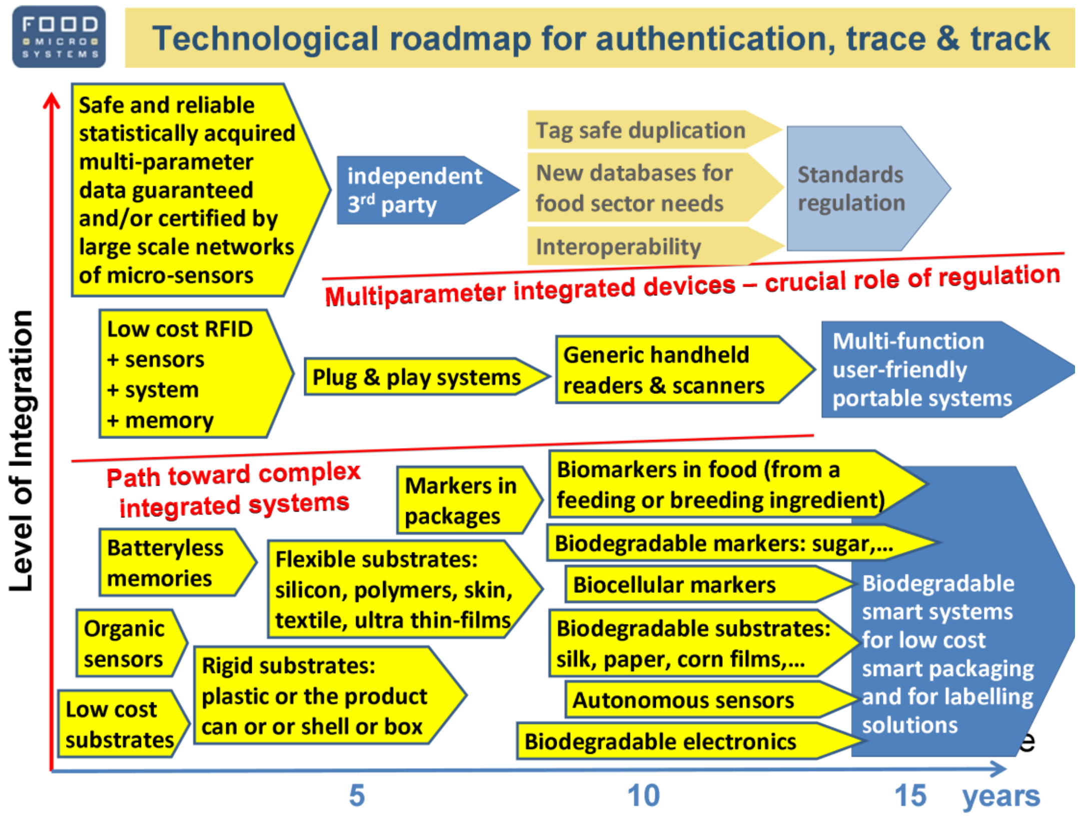


Fig.5-7 Technological breakthrough and global system approach for food sector

From a technological point of view, tracking and tracing face two major challenges. The first challenge is the capacity to develop interoperable data processing and sharing solutions. The definition of new standards and dedicated regulation is essential to achieve this goal. The second challenge is a technological one where innovative electronics need to be mass produced at very low price levels. The cost targets can be as low as mere fractions of a cent when fast moving commodities (e.g. fruits or vegetables) are to be tagged individually, and should not be above about 10 cents for luxury products or pallets containing many products. Development of flexible thin film plastics or polymers or tissues or even on biodegradable substrates will provide solutions to overcome two main barriers: massive use of labels in the food industry requires the price of the tags to stay in the cost target including sensing functions and second barrier. The sensing and storage of environmental parameters (temperature, CO_2 and other gases, humidity, some pathogens) will have to be achieved without making use of a self-powering means, to suppress the highly polluting electronic components from future disposable smart products. A breakthrough may emerge from fully recyclable and biocompatible solutions (e.g. sugar cell battery packaged in biodegradable containers and using bio-degradable electrical contacts).

6 Business case: the company "Alpha MOS"

Through the example of the company Alpha MOS, we illustrate in this section a real business case of a successful commercial exploitation of MST solutions in the food sector.

6.1 Description of the company and target market

The company Alpha MOS is an example of commercial success of sensory analysis instrumentation based on sensors and microsystems. The company was founded in 1993 and is the first company to introduce e-noses on the market. Today Alpha MOS is listed on the Paris stock exchange. During the last two decades some different systems have been developed not only for aroma determination but also extended for taste and vision. The company has developed sensing technologies that digitize the human senses and is now the first global provider of sensory instrumentation for authentication and certification, quality control and product development for different sectors, food and packaging being the most important with 50% of sales, according to their publicly available data:

- Food and Packaging: 50%
- Environment: 20%
- Pharmaceutical: 15%
- Cosmetics and Perfumes: 15%

Overall, Alpha MOS has sold around 1,700 instruments and prizes are in the range of 20,000 to 100,000 Euros depending on the complexity of the system.

6.2 Needs and demands

Odour and taste are key characteristics in sensory evaluation of many products. The sense of smell perceives odour-related volatile organic compounds. Odour analysis is all the more important as, according to many scientific publications, 80% of the perception of taste is actually a perception of odours by retro-olfaction. In a similar way an electronic tongue may replace in some analytical activity the human tongue by perceiving the savours among which the basic tastes (sweetness, saltiness, sourness, bitterness, umami).

In industrial food and beverage sectors there is a need for using systems that replace complex and time consuming laboratory systems for determining and monitoring quality attributes, safety defects and monitoring the whole production chain. These systems should be able to replace human intervention in tedious and repetitive aroma and taste evaluations. E-noses and e-tongues can play a role in this market.

The use of sensory instruments may bring the following advantages:

• Objective, automated and reliable taste/odour/aroma measurement produced from instrumental analysis
• A means to avoid testing of unpleasant substances for sensory panel assessors
• No more health safety issues related to human tests
• Fast delivery of results for taste/aroma/odour profiling
• Very sensitive techniques for taste measurement

Microsystems impact on the Alpha MOS products

Reliability, portability, automation and low cost are key specifications for modern analysis instruments. Thus, the development and application of micro and nano technologies is an important activity for Alpha MOS. Today gas and chemical microsensor arrays are key components of some of their sensory systems. MST devices are combined with sampling, automation, signal amplification and chemometrics and they end-up with highly performing analytical instruments that are currently on the market. A step forward is that with these systems the company offers analytical services in their laboratories. In addition based on the company R&D and know-how, a variety of customised services are provided. In conclusion this shows that, e-nose and e-tongue systems are typical examples of already successful instruments based on microtechnologies that show a high added value when they are part of complete performing systems, including customer support services. This is graphically shown in figure 3.11

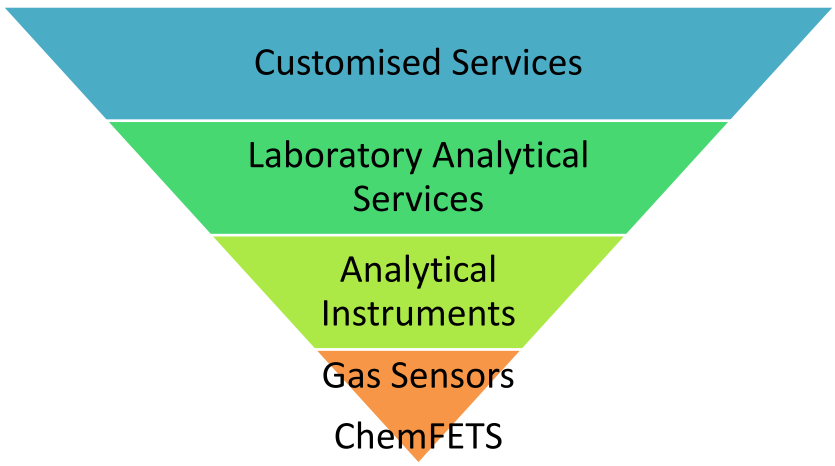


Figure 3.11: Graphical description of the enabling effect of the Microtechnologies in the field of gas and chemical sensors for the e-nose, e-tongue complete value chain.

6.3 Added value and use by the food and drink industry

e-nose and more generally sensory instrumentation are considered small niche markets and thus, Alpha MOS has applied a business model that aims at broadening the range of products and increasing their added value for the food and beverage end-users, depending on their needs and financial capabilities:

- Developing a variety of e-noses with different performances and degree of complexity in order to cover different applications. In this sense, some e-noses are available for on-line and off-line use.
- Developing not only e-noses but also e-tongue and e-eyes and gas micro-chromatographers to complement food and beverage monitoring tools.
- Developing systems that combine the performances of these systems, for higher added value applications.
- Growing business by also providing analytical services with their own instruments and laboratory services to the possible clients that are not interested in buying a complete system.
- Developing customized services for special applications and customers.

In summary, having a specific knowledge in chemical and sensory analysis, Alpha MOS provides a full range of solutions that cover the whole value chain in the analytical sensory instrumentation.

The following table summarises the main families of instruments developed by Alpha MOS based on Microsystems devices and the main specifications.

Four different families of e-nose are available of different complexity and for all type of applications. For the most complete e-noses they are combined with Gas Chromatography capabilities, which allow performing overall odour profiling and chemical composition analysis in one run. These complex systems available for detecting a wide range of volatiles compounds use several cross selective gas sensors of different types and rely on proprietary powerful on purpose software. For the simplest systems, e-noses are based on arrays of microfabricated metal oxide gas sensors (MOX). Different sets of sensors are available for the systems and the number of devices implemented in the arrays also vary (up to 18 sensors), according to the sensing requirements.

In a way similar to the human tongue, the Alpha MOS electronic tongue performs a global taste assessment of a complex mixture of dissolved organic or inorganic compounds. The electronic tongue not only assesses basic tastes (sweet, bitter, sour, salty, umami) but also all other gustatory components (metallic, pungent, astringent, etc.). Alpha-MOS e-tongues are based on microfabricated ChemFET sensor technology (Chemical modified Field Effect Transistor) using potentiometric measurement: 7 cross selective liquid sensors sensitive to ionic, neutral & chemical compounds responsible for taste. A special set of sensors is available for food and beverage analysis. Special software is also key to e-tongue systems.

Instrument Family	Microsystems Contents	Main Specifications
e-nose	Low cost Metal Oxide Gas sensor arrays (MOX), among others	• Reliable identification of compounds • Ultra-fast analysis: 3 to 8 minutes. • High sample throughput without any loss of resolution. • High sensitivity (down to low ppb), even on highly volatile compounds.
e-tongue	Low cost Chemical Field Effect Transistors arrays (ChemFETs).	• Taste measurement in liquid matrix: analysis of liquid products or solids dissolved in a liquid. • 2-standard sets of taste sensors available: one for food & beverage applications. • Reproducible and reliable taste evaluation. • Full & automated sensor analysis procedure. • Fast analysis: 3 minutes per sample.

Despite e-nose and e-tongue systems being mainly bench-top systems, e-nose instruments that can be used on-line and off-line are available. The tools can be applied in almost all points of the production chain.
Using the developed chemical and sensory analysis instruments, a wide variety of applications on raw materials, food ingredients, processed food, beverages and food packaging have been successfully achieved in various areas.

6.4 Main barriers

Main barriers for current e-nose and e-tongue systems are:

- Cost of systems
- Specificity for the applications and reliability
- Need for systems better suited to on-line application instead of off-line. Demand for higher automation, simplicity of use, etc.
- Lack of awareness of the current products and associated services among the end-users.

By developing and selling not only instruments but also providing services to the end users that cannot afford or are interested in purchasing their products, the company is expanding its business model to providing services next to products. Rather than only an instrument seller, Alpha MOS supports customers to do their analysis, either by selling them equipment, or by providing a testing service. This might be a relevant notion for food microsystem development for food. Where in the past many companies sold products, there is a broader trend towards organising the outcome demanded by the customer. Food industry is looking for food tests (demand) not for an expensive facility (means). As similar shift in business model can be seen in office supplies where copier and printer companies now claim to sell printing solutions (instead of printers).

From the technological point of view, any advantage that microsystems technologies can bring to solve these issues will be welcome in the research and development on gas and biochemical sensors for food and beverage applications in the next years.

When considering future directions, it has to be taken into account that the improvement of the microtechnologies will probably occur in parallel with even more important advancements of other types of technologies involved: biotechnology, signal amplification, data processing, software development, sampling, robotics automation, etc. Some advances made in microelectronics might be made redundant, supplanted but could also be supported by such developments.

7 Conclusion: microsystems in the food sector - how to make it happen?

At the beginning of 2013, the EU food sector experienced a crisis caused by the fraud of meat traders. The origin of this “meat adulteration scandal” is the mislabelling of horse meat into beef meat; especially beef intended to be ground and processed. The crisis showed that meat relabeling could easily be done in processing plants. It underlined weaknesses in the traceability systems and it triggered the implementation of an EU-wide testing campaign (7,259 tests were carried out in the 27 EU countries[9]). To date no rapid DNA test to ensure the origin of raw food materials has been made available commercially. This may in part be, because at the time of the crisis there were no cheap DNA tests readily available in large quantities that could distinguish beef from other meat. The use of microsystems could help to reduce costs, time and make it possible to reinforce controls and avoid such scandals in the future.

Food process innovation and improved process control are an important focus for microsystems for food. Safety and Quality issues are important as well but they are usually performed ex-post when there is little margin to corrections. From a technology point of view, process control scenarios may involve similar measurements that in safety and quality with the additional demand of performing them more often. From this particular perspective, microsystems will be accepted in process control applications when they are good enough to enable or anticipate corrective measures that will save quality and safety problems and loss of product in a way that is not currently possible. As in many other applications, innovation will emerge when technology push meet application pull. In process control scenarios, this means for microsystems:

- Sufficient miniaturisation, automation and multiparametric response to enable at-line punctual analysis low cost enough (offering a competitive cost per parameter when compared with current analytical alternatives, if existing). This trade-off is pretty much similar to the situation of microsystems for food quality and safety assessment.
- Stability, robustness and (in some cases) autonomy to enable in-line/on-line continuous monitoring whereas is of practical and economical sense.
- Communications capabilities to integrate them with other cooperating elements in an overall process management system in (practical) real time.

In this way, microsystems will effectively contribute to the answer the food industry challenges to guarantee food safety, to reduce its environmental impact while guarantying an affordable supply to an increasing population.

[9] http://ec.europa.eu/food/food/horsemeat/tests_results_en.htm

Throughout the *FoodMicroSystems* project it was realised that one of the most important factor in influencing the adoption of microsystem-based devices by the food industry is the cost. Current prices for example for RFID are too high to label individual products in most food sectors. However, by using RFID for shiploads, the demand for the specific RFID would be too low to produce these tags at reasonable prices.

The prices of equipment price depend on quantity produced and the quantity commercialised depends on the price: we thus face a “chicken and egg situation”. Part of this problem could be overcome by the use of “platform technologies” – standardised components or systems that can be produced in high volumes and adapted or re-configured to a range of application settings to measure or sense a multitude of parameters. Those multifunctional smart systems would be re-usable or usable across different products - this would allow the needed demand for large scale production. Another boost for microsystems may also come from the regulatory bodies, by defining new guidelines that allow the use of new microsystem-based reference measurements instead of traditional laboratory methods only.

To further develop promising approaches and their successors as identified in the roadmaps, both, motivations and investments are needed. Horizon 2020 can provide adequate support for this. *FoodMicroSystems* recommends in particular to use its roadmaps in the work programme of the **Specific Challenge 1.2: Smart System Integration** (under the ICT programme "Leadership in Enabling Industrial Technologies " LEIT) and to use the **pre-commercial procurement** for supporting the development of solution to be implemented by food safety authorities.