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Novel Approaches for Food Safety Management and Communication

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Abstract

The Current safety and quality controls in the food chain are lacking or inadequately applied and fail to prevent microbial and/or chemical contamination of food products, which leads to reduced confidence among consumers.

On the other hand to meet market demands food business operators (producers, retailers, resellers) and regulators *need* to develop and apply structured quality and safety assurance systems based on thorough risk analysis and prevention, through monitoring, recording and controlling of critical parameters covering the entire product’s life cycle.

However the production, supply and processing sectors of the food chain are fragmented and this lack of cohesion results in a failure to adopt new and innovative technologies, products and processes.

The potential of using Information Technologies in tandem with data science in the food chain will provide stakeholders with novel tools regarding the implementation of a more efficient food safety management system.

Introduction

At the dawn of the 21st century, the agro-food industry is facing the following main challenges: (i) having enough to eat (*Food Security*) and (ii) ensure that it is safe to eat (*Food Safety*). These objectives should be realized not only in an environment of tremendous technological progress and evolution of consumers' life-styles, but also of economic problems, in which the food industry is called to operate under seemingly contradictory market demands.

Regarding *Food Safety* along the food chain, it is well known to be a shared responsibility among *Food Business Operators*, *Authorities* and *Consumers* [1]. Thus, Food business operators are challenged to combine requirements from different stakeholders, such as government, retailers, while the international resolutions of the Uruguay Round of the General Agreement on Tariffs and Trade (GATT) in 1995 [2], recognized public health risk as the *only* basis for restrictions of international trade in food, into the food industry. However, within the food chain from farm to consumer, food commodities may be exposed to multiple hazards that may cause physical, biological or chemical contamination to food and consequently increase the risk of consumption of contaminated food. These risks, e.g., pathogenic bacteria [3], mycotoxins [4] biogenic amines [5] or possible carcinogenic compounds such as caramel colours [6], have created mistrust of governments and industry by the European consumer that is threatening to become a long-term problem.

Food waste and misuse has been reported [7] to be probably the greatest problem concerning food security; indeed roughly 1/3 of food produced for human consumption is lost or wasted globally and within the EU more than 100 million tonnes of food are wasted annually [European Community; Food Waste [8]. Food spoilage mainly due to microbial activity [9] is one of the most significant threats to food security. Thus minimization of food loss, as well as assurance of quality and safety [10] can be considered as the ultimate goal for the food industry.

To remedy this, the food industry and other stakeholders (e.g., competent authorities, retailers) have to provide increased vigilance with regard to food safety and quality issues. Consumers need to be and feel reassured that Food industries, as well as Food authorities, are taking extra measures to guarantee the safety of foods.

The objectives set out in the White Paper on Food Safety [1] dealt with *(i)* improvement of the efficiency and coherence of the EU food legislation, particularly in the area of food safety, *(ii)* restoring consumer confidence by the above measures and improving the quality of information available to consumers, and *(iii)* extending the scope of the EU food regulation by developing an EU-wide nutrition policy. To achieve these objectives in the area of food safety, a number of guiding principles have been applied, namely ***(1)*** adoption of the precautionary principle, ***(2)*** extending the scope of food safety regulation across the entire food chain from 'farm to fork' including, for example relevant controls on animal feed, ***(3)*** attribution of primary responsibility for safe food production to industry producers and suppliers within the context of the EU legislation, ***(4)*** setting out clear responsibilities for public bodies by defining standards for the food industry to meet and monitoring industry compliance, ***(5)*** establishing traceability as a major responsibility in food production and a prerequisite to both food safety and effective consumer choice.

Current Food Safety Management System

Nowadays a wide range of chemical and microbiological analyses has been proposed to evaluate the quality or safety of raw or processed materials and food products [11]. Currently, the safety of food relies heavily on regulatory inspection and sampling regimes [12]. Indeed the current Food Safety Management System, although largely based on good design of processes, products and procedures, end or finished product testing (analysed for certain hazards), is considered to be the control measure of the production process (Fig. 1). This is evident in the case of microbiological food safety where specific microbiological analyses should be followed.

These microbiological analyses can be implemented with conventional microbiology (e.g., colony counting methods) or molecular based techniques that are considered more reliable and accurate [13,14,15,16]. Chemical analyses are also used to monitor safety and quality of foods. These analyses either microbiological or chemical have certain disadvantages, as they are (i) time-consuming providing retrospective results, (ii) costly, (iii) few require high-tech molecular tools and thus highly trained personnel, and (iv) usually destructive to test products, limiting thus their potential to be used on-, in- or at-line [14, 17].

Furthermore, in the case of molecular tools, results may be misleading, as these techniques are focused so far on pathogenic rather than specific groups of the microbial association, which contribute to spoilage depending on storage and packaging conditions [16]. The molecular approach is also costly, as high-tech instruments are required. In addition, due to the complexity of molecular techniques, the number of verified samples/measurements in many cases is severely limited.

It is evident that end-product analyses (testing) provide only very limited information on the safety status of a food, since the presence of a hazardous organism could give an indication but absence in a limited number of samples is no guarantee of safety of a whole production batch. Thus, finished product testing is often too little and too late. On the other hand, efforts have been made to replace both conventional and molecular microbiological analyses with detection of biochemical changes occurring in food that could be used to assess food spoilage or safety. This approach, however, seems inadequate because it cannot sufficiently guarantee consumer protection, since 100% inspection and sampling is technically, financially and logistically impossible. Thus it is inevitable that new strategies should be designed and implemented focusing on the management and control of the hazards in a more proactive way by implementing an effective food safety management system and/or approaches. Indeed a modern food quality and safety assurance system should not be based on end-product analyses (Fig. 1). Instead, prevention rather than inspection, through monitoring, recording and controlling of critical parameters during the entire food's life cycle should be developed and implemented. The food life cycle should be extended beyond at and post processing phase, to include, retailer and even consumer's storage and preparation facilities.

Process Analytical Technology (PAT): Implementation in food industries.

To contribute in assurance of food safety, on and post-processing food industries and food business operators focus on the implementation of an effective Food Safety Management System (FSMS) [12], which is based on controlling, monitoring, and recording the critical parameters. On the other hand, the 'accepted' wisdom in the food industry is that processes cannot be modified as there is limited understanding of the potential impact of change and therefore re-registration would be required to demonstrate that a modified process still produces the right product from the right raw materials. Additionally, post-production testing is in use today as a means to reject off-specification foods or to comply with certain legislative regulations, from processes that might be "out of control" (Fig. 1). Process control aims to avoid any batch-to-batch changes in the raw materials, process conditions and equipment.

The Process Analytical Technology (PAT) concept, originated from the desire of the (bio) pharmaceutical industry regulators to shift product quality control towards a science-based approach, is proposed for the food industries [17] aiming at the: (i) optimization of food quality, (ii) reduction of food waste through a more efficient control of the processes, taking into account all processing steps and integrate sensors at the Critical Control Points (CCP), (iii) reduction of the risk to consumers by controlling manufacturing based on process understanding.

PAT can be considered as a framework for: (i) designing, analysing, and controlling manufacturing through timely measurements, (ii) processing of critical quality and performance attributes of raw and in-process materials and processes, (iii) process measurement, information management tools, feed forward-feed backward process control strategies, product & process design and optimization strategies, and (iv) reducing variation in manufacturing.

The PAT approach will offer a solution to a broad need identified by food industries (i.e., safety & quality of raw and in process materials), since:

- Food business operators will be better prepared to minimize risk as a result of rapid identification and control of potential hazards

- Food industries that rely heavily on timely preventive control measures will also benefit, since they will minimize the time needed to decide on the production and distribution of particular food batches
- Food producers will increase their market shares by improving their retailers' and distributors' satisfaction offering novel and easy-to-use means through ICT technologies and thus reassuring customers about the quality and safety of the food products they are about to buy

It needs to be stressed that the high pressure exerted from stakeholders (such as consumers and regulatory authorities) to the food industry to produce safe and high quality products, at low cost, minimizing additives and preservatives in a sustainable manner, will force food producers to constantly develop new PAT implementations, in which food safety policy will be taken into consideration. Indeed PAT envisages, a scientific, risk-based, holistic and proactive approach to the food industry, with a deliberate design effort from product conception through commercialization, in which there will be a full understanding of how product attributes and process relate to product performance. There are two steps needed for such an approach; the 1st is the "Product & Process Design and Development", in which the upfront desired product performance should be defined and the Critical Quality Attributes (CQA) should be identified; the 2nd step is a continuous risk assessment and risk control with regard to the impact of (i) material attributes and process parameters on product CQAs, (ii) identification and control sources of variability in material and process, and (iii) monitoring (continuously) and updating process to assure consistent quality.

So far the limited application of PAT in food industries [17], has narrowed down to predominantly focusing on non destructive analytical instruments, spectroscopic sensors based on vibrational spectroscopy, e.g. NIR, fluorescence, Raman, FT-IR, or on surface chemistry, e.g. hyper and multispectral devices which are becoming increasingly affordable and can be associated with advanced computational processing (SVM, ensemble DLS-PCA) losing however the original holistic view [17,18]. This view is that measurements in PAT are not just an 'analytical' measurement such as pH, water activity, metabolomics through HPLC, GC or GC/MS, spectra through spectroscopy, but all those measurements can be used to infer or relate to product quality with the goal to (i) understanding of the process, (ii) identification of CCP, (iii) application of knowledge base to control the process. ▯

The term "analytical" in PAT is considered to be viewed broadly to include chemical, physical, microbiological, mathematical and risk analysis conducted in an integrated manner, in which Information Technology (IT) will have a major role to: *(1)* "enhance understanding and control manufacturing process" promoting in this way an ideology in which "quality cannot be tested into products; it should be built-in or should be by design", and *(2)* incorporate advanced measurements related to the above mentioned tools, communication systems, i.e. integration of diverse components into ubiquitous and global network; achieving reliability and security in this network.

The introduction of innovative technologies in PAT approach is one of the determining factors in future growth and increased competitiveness of food industries.

Recently, some interesting analytical approaches have been forwarded for non-destructive rapid methods, which provide means to quantitatively monitor characteristics of food safety and quality (Fig. 2).

Such methods include biosensors (enzymatic reactor systems), electronic noses (sensor arrays), Fourier transform infrared (FT-IR) and Raman spectroscopy, as well as imaging platforms. However, due to mass data generated for each sampling point, conventional and manual approaches to interpret the output can be extremely challenging. For this reason, such platforms are often used in tandem with advanced statistical methods to reduce the dimensionality of the initial variables to a smaller number of factors that can be used as potential biomarkers for quality and safety.

With the evolution of data science and machine learning approaches, novel computational methods emerged to rapidly provide information related to food safety and quality or categorization of foods with regard to spoilage, through the development of classification or regression models using spectral or imaging data for model training and validation [18,19].

Machine learning methods are generally classified into two main groups; *unsupervised* and *supervised* learning. For unsupervised learning, no prior knowledge is assumed about the data; in other words, samples are clustered according to their similarity in the measured profiles. This includes k-means clustering, hierarchical clustering and association analysis [20]. On the other hand, in supervised learning the model is trained using an input learning (training) subset, in order to unravel hidden patterns within the data to predict a target variable or class. The prediction can be either a nominal value (classification model), or numeric value (regression model). Algorithms belonging to this category include neural networks, fuzzy logic, support vector machines and decision trees [18,20,21].

There is, however, a need to bridge the gap between the many emerging and rather promising devices, which could be used in the food industry in tandem with the appropriate data mining and analysis [22,23]. The outcome of this multidisciplinary and multi-dimensional data paradigm that integrates and crosses several scientific fields and sub-disciplines, such as process chemistry development, information technology, food science, food microbiology, molecular biology, process analytical chemistry, vibrational spectroscopy, bioinformatics, machine learning, chemical engineering, process systems and control engineering [14, 23,24,], will be for the benefit of Food Safety Management System.

Enhancing Food Safety Management System (FSMS) through the Information Technology; a new dimension

The issue of food safety is vital in recent years and although it is constantly reviewed in the light of new scientific evidence, its implementation is not always efficient in many different parts of the food chain. For example, systematic management of food safety *via* HACCP, GMP, etc., entails raw material selection, as well as control of conditions during processing and distribution [14,25], with the latter being the weakest link of the system. Indeed, conditions during transportation and storage at retail level are out of the manufacturer's direct control and often deviate from specifications. Temperature control is completely lacking from the store to domestic storage and until the time of preparation and consumption. Some quantitative evidence is available from studies and surveys at distribution, retail and domestic level to illustrate the magnitude of the problem [26]. In general, it is well established that *food handling and logistics,* can substantially contribute to the risk and exposure to certain food-borne hazards [26,27]. To face the weakest link in the food chain, the implementation of parameter quantification that allows the prediction of the behaviour of pathogenic bacteria or other hazards (mycotoxins) has been introduced in the food industry [28]. It should be stressed however that there is limitation on the accumulation of many different pieces of information, which is essential (1) to understand the rational for model development, and (2) model validation (if any) under isothermal conditions. In practice, however, temperature fluctuations may be frequent throughout food storage and distribution.

To address the issue, Information Technologies (IT), such as cloud computing and storage, big data, Internet of things, mobile web in combination with barcodes and smartphones, can be used to (i) offer the possibility to easily track the processes in the production, storage, transportation, retail, and even using phases of foods, (ii) tackle the important application of food quality (including safety) during processing [29 -33].

Indeed, Information Technology can assist food producers, retailers, authorities and even consumers to take better decisions by providing them with data and tools that enhance decision-making process, consequently allowing better management of the natural resources. To achieve this Cloud-computing platforms and the real-time monitoring and extraction of data safety and quality parameters and temperature profiles throughout the production chain can be of great importance. Such cloud platforms and data repositories should be coupled with appropriate web applications in order to assist producers with their investing and planning decisions. This basic concept and approach was adopted in Guizhou (China) province, where on the basis of the latest information technology, food production enterprises, government, testing organizations and consumers were integrated into a unified food safety information service cloud platform [34]. The core technology of the cloud platform is composed of food safety knowledge system, testing management system, food safety information publicity system, as well as mobile application. The food factory inspection data, government inspection data, testing organizations data and consumers purchasing information are integrated into food safety and nutrient test big data. Utilizing the data to explore the information that is needed by all the parties, can be served as a solution to the risk exchange problem faced by food stakeholders, while at the same time, the food safety problem can be solved through the contribution of different stakeholders.

Cloud computing can also be of great importance for the FSMS concept, as a means to store information associated with each product and make this information accessible to retailers and consumers via, e.g. platforms, barcodes such as QR codes (Fig. 3). Currently QR codes are frequently integrated within the food packaging system to direct consumer to a product web-page with more information about the given product such as origin, cooking instructions and suggested recipes. However, there is great potential to expand the usage of barcoding beyond simply pointing to a static web page; though tracing back the product to the collection of enormous data derived from the “connected” rapid and non-invasive analytical platforms within the PAT framework (Fig. 2). In this way, the combination of rapid methods with machine learning and barcodes will provide a valuable “real life” application of the technology in a new domain (food freshness and safety) that will contribute to the predicted increase in the cloud computing market. The concept of IT efficiency also embraces the ideas encapsulated in green computing, since not only are the computing resources used more efficiently, but further, the computers can be physically located in geographical areas that have access to cheap electricity while their computing power can be accessed long distances away over the Internet.

Barcodes and more specifically **QR codes** are becoming a standard consumer-advertising tool. They have been gaining an increased popularity over the past five years with the introduction of smartphones with embedded cameras and image processing packages. Nowadays, over half of EU citizens have a smartphone capable of capturing QR codes, and around 25% of smartphone users are already familiar with the process of scanning a QR code. We believe that in near future there will be a unique connection between dynamic cloud-based information and QR codes that will provide enormous information to food stakeholders (Fig. 3) as well as a massive boost e.g. the newer technologies of mobile visual search (MVS) and near field communication (NFC) but neither of these are suitable for providing additional information about specific product items.

On the other hand the **Internet-of-Things (IoT)** and emerging technologies (i.e., Wireless sensor network, cloud technology and machine learning) is a vision of connectivity for anything, anytime and anywhere, which may have a dramatic impact on our daily life as what the Internet has done in the past two decades [29]. This will have significant economic impact on each of the individual information technologies as it creates a previously untapped market for these technologies, but it will also demonstrate exciting new synergies between the technologies that will spark new ideas for future innovations.

Internet technologies allow supply chains to use virtualizations dynamically in operational management processes. This will improve support for food companies dealing with perishable products, unpredictable supply variations and stringent food safety and sustainability requirements. Virtualization enables supply chain actors to monitor, control, plan and optimize business processes remotely and in real-time through the Internet, based on virtual objects instead of observations on-site.

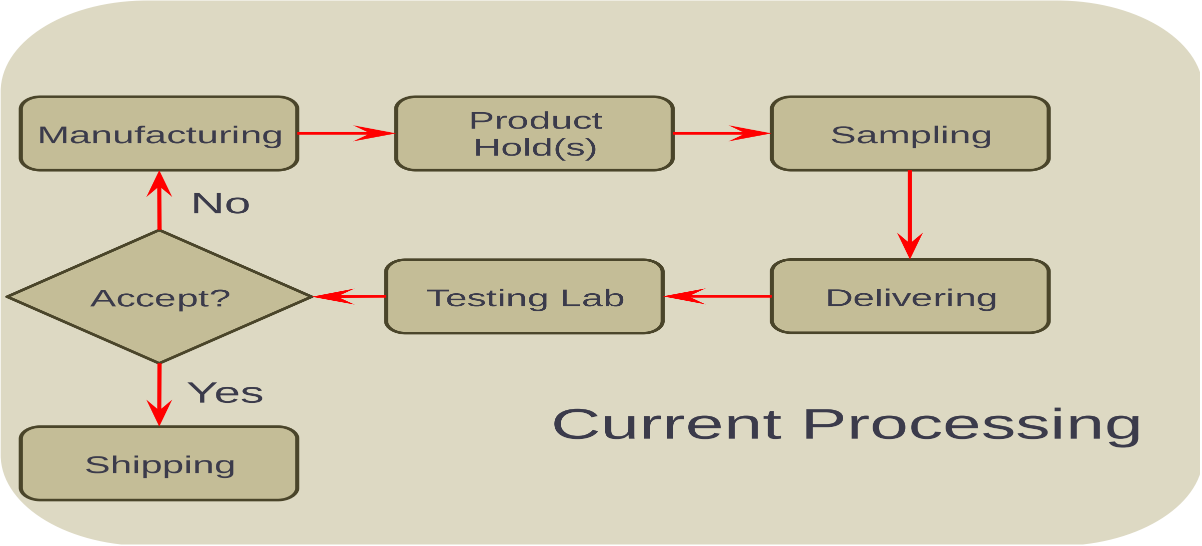

Fig. 1 Current testing and controlling of food safety

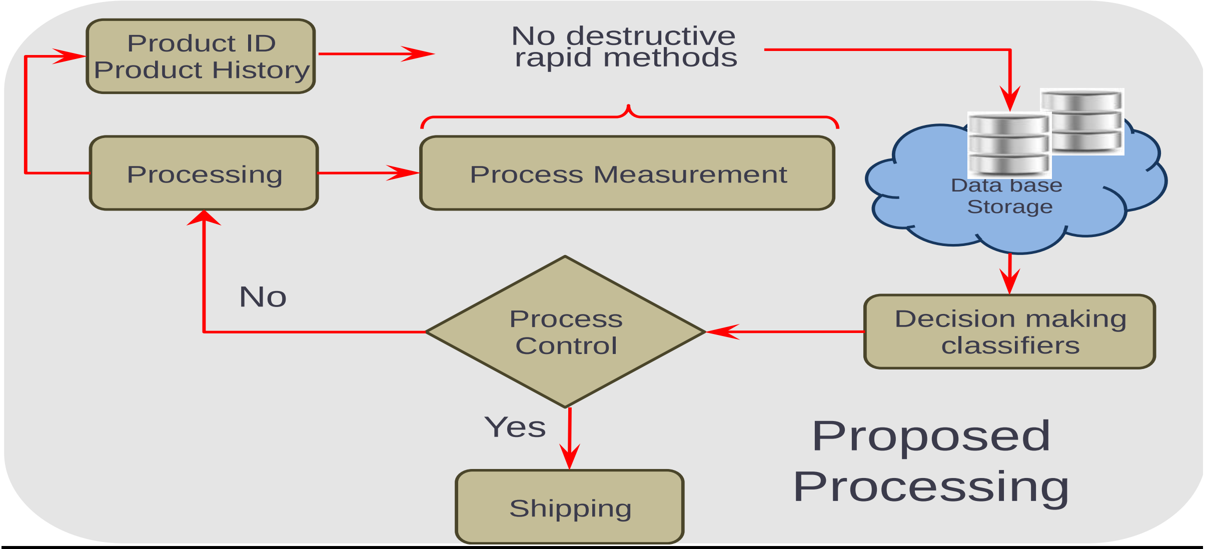

Fig 2. Use of non-destructive rapid methods for the implementation of PAT in food processing;

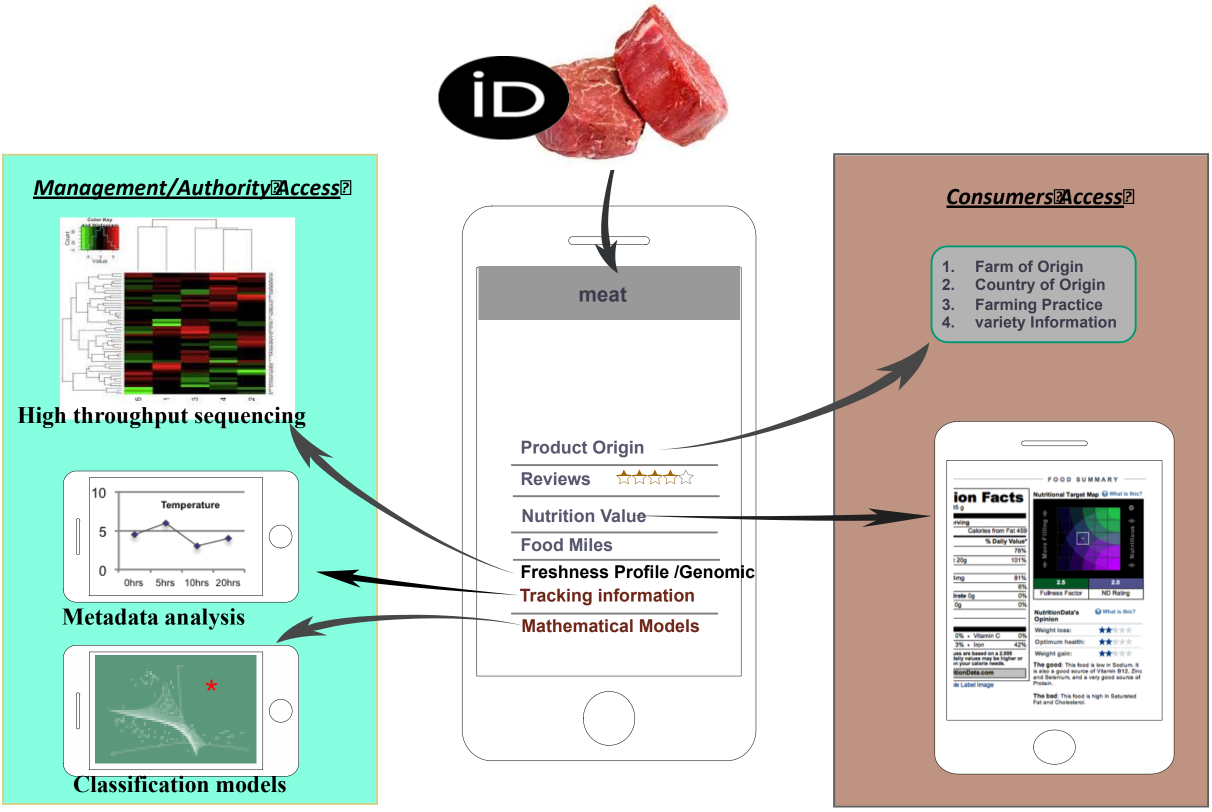

Fig. 3 Visual representation of barcode enabled –smart phone application

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