

1 **Novel Approaches for Food Safety Management and Communication**

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16 *food microbiology, food chemistry, metabolomics,*

19 **Abstract**

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

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

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

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

34

35 **Introduction**

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

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

55 Food waste and misuse has been reported [7] to be probably the greatest problem
56 concerning food security; indeed roughly 1/3 of food produced for human consumption
57 is lost or wasted globally and within the EU more than 100 million tonnes of food are
58 wasted annually [European Community; Food Waste [8]. Food spoilage mainly due to

59 microbial activity [9] is one of the most significant threats to food security. Thus
60 minimization of food loss, as well as assurance of quality and safety [10] can be
61 considered as the ultimate goal for the food industry.

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

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

80

81 **Current Food Safety Management System**

82 Nowadays a wide range of chemical and microbiological analyses has been proposed to

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

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

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

104 It is evident that end-product analyses (testing) provide only very limited information
105 on the safety status of a food, since the presence of a hazardous organism could give an

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

122

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

124 To contribute in assurance of food safety, on and post-processing food industries and
125 food business operators focus on the implementation of an effective Food Safety
126 Management System (FSMS) [12], which is based on controlling, monitoring, and
127 recording the critical parameters. On the other hand, the 'accepted' wisdom in the food
128 industry is that processes cannot be modified as there is limited understanding of the
129 potential impact of change and therefore re-registration would be required to

130 demonstrate that a modified process still produces the right product from the right raw
131 materials. Additionally, post-production testing is in use today as a means to reject off-
132 specification foods or to comply with certain legislative regulations, from processes that
133 might be “out of control” (Fig. 1). Process control aims to avoid any batch-to-batch
134 changes in the raw materials, process conditions and equipment.

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

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

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

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

152 - Food industries that rely heavily on timely preventive control measures will also
153 benefit, since they will minimize the time needed to decide on the production and
154 distribution of particular food batches

155 - Food producers will increase their market shares by improving their retailers'
156 and distributors' satisfaction offering novel and easy-to-use means through ICT
157 technologies and thus reassuring customers about the quality and safety of the food
158 products they are about to buy

159

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

175

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

187

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

196

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

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

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

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

214 Machine learning methods are generally classified into two main groups; *unsupervised*
215 and *supervised* learning. For unsupervised learning, no prior knowledge is assumed
216 about the data; in other words, samples are clustered according to their similarity in the
217 measured profiles. This includes k-means clustering, hierarchical clustering and
218 association analysis [20]. On the other hand, in supervised learning the model is trained
219 using an input learning (training) subset, in order to unravel hidden patterns within the
220 data to predict a target variable or class. The prediction can be either a nominal value
221 (classification model), or numeric value (regression model). Algorithms belonging to

222 this category include neural networks, fuzzy logic, support vector machines and decision
223 trees [18,20,21].

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

233

234 **Enhancing Food Safety Management System (FSMS) through the Information** 235 **Technology; a new dimension**

236 The issue of food safety is vital in recent years and although it is constantly reviewed in
237 the light of new scientific evidence, its implementation is not always efficient in many
238 different parts of the food chain. For example, systematic management of food safety *via*
239 HACCP, GMP, etc., entails raw material selection, as well as control of conditions during
240 processing and distribution [14,25], with the latter being the weakest link of the system.

241 Indeed, conditions during transportation and storage at retail level are out of the
242 manufacturer's direct control and often deviate from specifications. Temperature
243 control is completely lacking from the store to domestic storage and until the time of
244 preparation and consumption. Some quantitative evidence is available from studies and
245 surveys at distribution, retail and domestic level to illustrate the magnitude of the

246 problem [26]. In general, it is well established that *food handling and logistics*, can
247 substantially contribute to the risk and exposure to certain food-borne hazards [26,27].
248 To face the weakest link in the food chain, the implementation of parameter
249 quantification that allows the prediction of the behaviour of pathogenic bacteria or
250 other hazards (mycotoxins) has been introduced in the food industry [28]. It should be
251 stressed however that there is limitation on the accumulation of many different pieces of
252 information, which is essential (1) to understand the rationale for model development,
253 and (2) model validation (if any) under isothermal conditions. In practice, however,
254 temperature fluctuations may be frequent throughout food storage and distribution.
255
256 To address the issue, Information Technologies (IT), such as cloud computing and
257 storage, big data, Internet of things, mobile web in combination with barcodes and
258 smartphones, can be used to (i) offer the possibility to easily track the processes in the
259 production, storage, transportation, retail, and even using phases of foods, (ii) tackle the
260 important application of food quality (including safety) during processing [29 -33].
261
262 Indeed, Information Technology can assist food producers, retailers, authorities and
263 even consumers to take better decisions by providing them with data and tools that
264 enhance decision-making process, consequently allowing better management of the
265 natural resources. To achieve this Cloud-computing platforms and the real-time
266 monitoring and extraction of data safety and quality parameters and temperature
267 profiles throughout the production chain can be of great importance. Such cloud
268 platforms and data repositories should be coupled with appropriate web applications in
269 order to assist producers with their investing and planning decisions. This basic concept

270 and approach was adopted in Guizhou (China) province, where on the basis of the latest
271 information technology, food production enterprises, government, testing organizations
272 and consumers were integrated into a unified food safety information service cloud
273 platform [34]. The core technology of the cloud platform is composed of food safety
274 knowledge system, testing management system, food safety information publicity
275 system, as well as mobile application. The food factory inspection data, government
276 inspection data, testing organizations data and consumers purchasing information are
277 integrated into food safety and nutrient test big data. Utilizing the data to explore the
278 information that is needed by all the parties, can be served as a solution to the risk
279 exchange problem faced by food stakeholders, while at the same time, the food safety
280 problem can be solved through the contribution of different stakeholders.

281
282 **Cloud computing** can also be of great importance for the FSMS concept, as a means to
283 store information associated with each product and make this information accessible to
284 retailers and consumers via, e.g. platforms, barcodes such as QR codes (Fig. 3). Currently
285 QR codes are frequently integrated within the food packaging system to direct consumer
286 to a product web-page with more information about the given product such as origin,
287 cooking instructions and suggested recipes. However, there is great potential to expand
288 the usage of barcoding beyond simply pointing to a static web page; though tracing back
289 the product to the collection of enormous data derived from the “connected” rapid and
290 non-invasive analytical platforms within the PAT framework (Fig. 2). In this way, the
291 combination of rapid methods with machine learning and barcodes will provide a
292 valuable “real life” application of the technology in a new domain (food freshness and
293 safety) that will contribute to the predicted increase in the cloud computing market. The

294 concept of IT efficiency also embraces the ideas encapsulated in green computing, since
295 not only are the computing resources used more efficiently, but further, the computers
296 can be physically located in geographical areas that have access to cheap electricity
297 while their computing power can be accessed long distances away over the Internet.

298

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

310

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

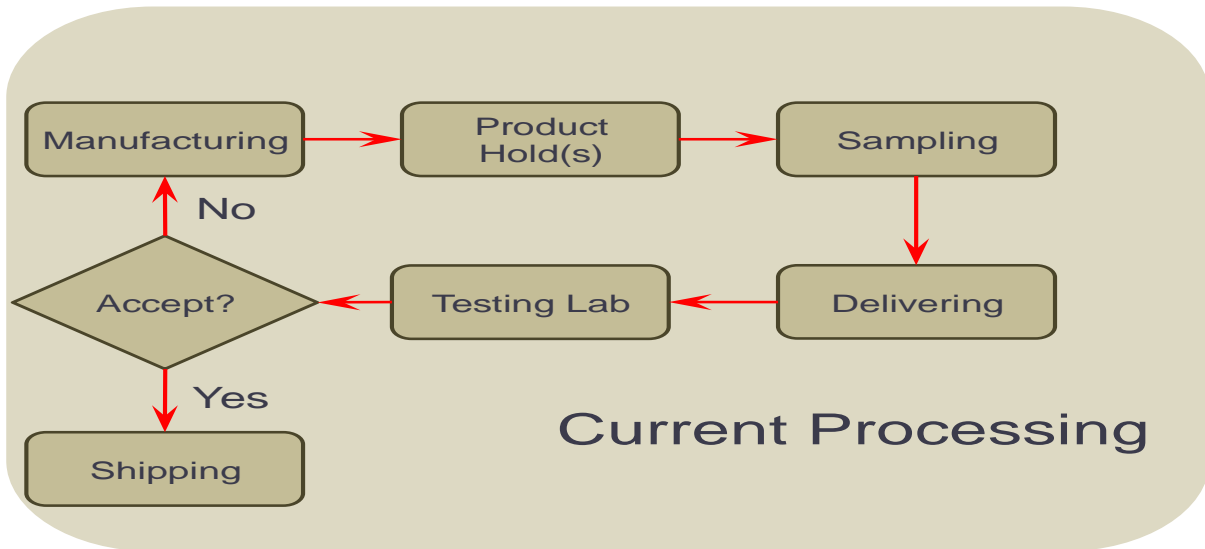
317 demonstrate exciting new synergies between the technologies that will spark new ideas
318 for future innovations.

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

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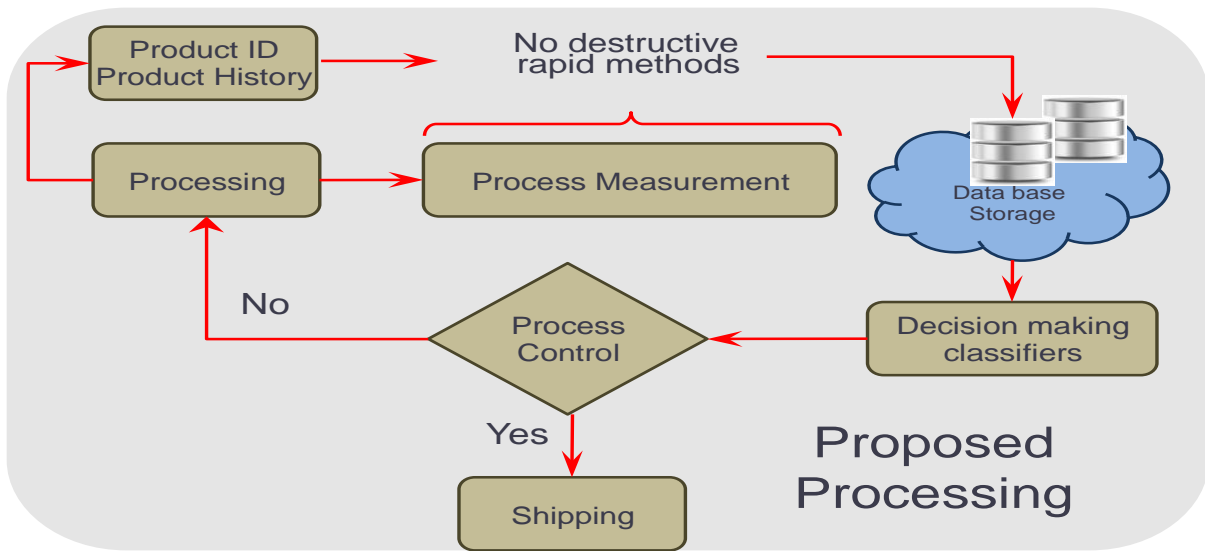
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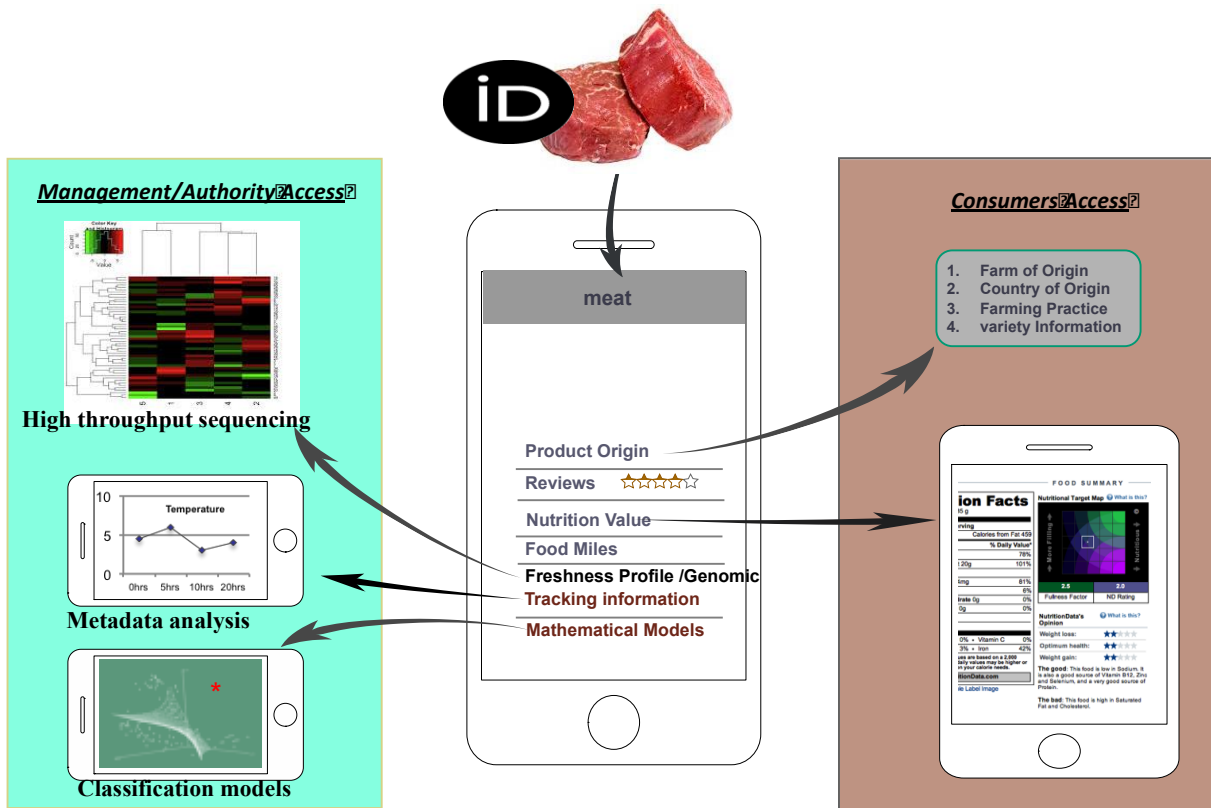
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Fig. 1 Current testing and controlling of food safety



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



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

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