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State-Of-The-Art and Future Trends of Information and Communication Technologies in Agri-Food Sector: A World-Wide Review

Marco Pellegrini

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Department of Agricultural, Food and Environmental Sciences, Università Politecnica delle Marche, Via Brecce Bianche 10, 60131 Ancona, Italy. LIF Srl, Via di Porto 159, 50018 Scandicci (FI), Italy. E-mail: marco.pellegrini@ieee.org.

ABSTRACT

World population is expected to grow considerably by the end of this century and in particular, the number of people living in the least developed countries is estimated to triple. As a consequence, also the food production will have to increase. Beyond production, feeding an increasing population brings new challenges in terms of food safety and quality but, at the same time, also opportunities for human and technological development. In the next future, food science will have to focus on developing sustainable and ecological technologies, taking into account modern developments in neighboring fields of science and engineering. In this framework, Information and Communication Technologies (ICTs) can play a key role in ensuring an inclusive development of agri-food chains. The objective of the present study is twofold: to review the state-of-the-art of using ICTs in food technology and to outline how the evolution of these technologies could be useful for the whole agri-food sector. Wireless communication networks, intelligent sensors and embedded systems software will be increasingly pervasive in the food industry. United Nations (UN) 2030 Agenda provides many business opportunities for both information technology and food industries but standardization and interoperability between different technologies are major challenges to a fair development of ICTs. In order to promote reusability, reliability, scalability and platform independence, future investments related to ICTs in agri-food sector should be focused on solutions independent of any vendor or specific product; by embracing such an approach, even developing countries can benefit from technological progress.

Keywords: Agri-food, Food quality, Food safety, Information and communication technologies

INTRODUCTION

The current world population is counted at 7.6 billion people and it is expected to grow considerably in this century, reaching 9.8 billion in 2050 and 11.2 billion in 2100. Such growth would not be uniform, it is expected to happen mainly in Less Developed Regions (LDR) and in particular in the least Developed Countries (LDC). Indeed, the population of LDC is expected to triple by the end of the century (United Nations, 2017a). As a consequence, also the supply of food will necessarily have to grow. Two of the 17 Sustainable Development Goals (SDGs), promoted by the UN 2030 Agenda for Sustainable Development (United Nations, 2017b), aimed at ending hunger, food insecurity and malnutrition for all, and promoting sustainable industrialization (SDG 2 and 9). Since SDGs can only be achieved with involvement of the private sector working alongside Governments and the UN system (United Nations Global Compact Office and KPMG International Cooperative, 2016), feeding an increasing population brings new challenges in terms of production, safety and quality. There are several barriers to addressing these challenges; first, constraints in changing consumer behavior, together with the limited innovation in food product development and distribution reduce the ability to shift consumer demand towards more nutritious and sustainable diets. Then, inadequate infrastructures and financial inclusion make it difficult for farmers to gain access to cost-effective products, services and information that could boost their productivity and profitability. Next, the lack of transparency along supply chains has resulted in a loss of consumer trust. Lastly, the high cost of developing crop technologies has reduced crop diversity, generating both dietary and environmental consequences (World Economic Forum, 2018). Although these barriers are considerable, the Fourth Industrial Revolution (4IR) technologies are making it easier to dismantle some of them. Taken together, these innovative technologies lower cost to scale, accelerate innovation, increase transparency in food systems, enable consumers to make informed choices, and allow policymakers to engage in evidence-based policy making (World Economic Forum, 2018). Until recently, the global food industry has been focused on the availability of food but concerns about food safety and sustainable development are becoming increasingly important (Connor, 2016).

In the next 30 years, the food supply system must be able to develop along an ecological public health framework (Lang, 2009), guaranteeing the balance between availability of food and its health and nutrition requirements without compromising Earth's natural resources (Connor, 2016). Current innovations in food production, safety and quality come from the development of novel tools, technology and knowledge and their use in the food industry. Food engineering (FE) is the application of engineering principles to the storage, processing and distribution of food materials and their bio-products (Texas A and M University, 2018); from the farm to the consumer it combines microbiology, chemistry, applied physics and engineering for food and related industries. The major challenge which FE faced is to provide sufficient, safe and nutritious food to all people around the globe. Moreover, the food which is offered to the worldwide community of consumers has to be socially and economically accessible (International Union of Food Science and Technology, 2012). Therefore, food science community must develop an integrated approach with agriculture and nutrition in order to achieve sustainable raw materials production, processing and targeted nutritional concepts (International Union of Food Science and Technology, 2012). In the next future, FE should focus on the development of sustainable and ecological food production and processing technologies, taking into account modern developments in neighboring fields of science and engineering.

In this framework, there is ample empirical evidence showing that the use of information and communications technologies (ICTs) can produce better results in the area of agricultural development (Chavula, 2014). ICTs play a key role in ensuring a sustainable and inclusive development of agri-food chains (Pellegrini and Mozzon, 2018b), and in fostering local, national and global food security by enhancing production and productivity, lowering operating costs, facilitating access to markets, information, credit, and capacity-building (International Telecommunication Union, 2017). It is known that information technology can be used to influence consumers' food choices improving nutrient intake and impacting consumers' health and consequently public health (Lewis and Burton-Freeman, 2010) various types of devices are indeed being used in food retail outlets, restaurants, and at home that provides feedback to consumers based on their food selections, self-scanners provide nutrition information that may alter food choice on the spot, some food retail outlets have begun to use loyalty cards to alert users about recalled foods and are also educating consumers about the nutrition profile of foods purchased. ICT is an extensional term for information technology (IT) stressing the importance of the integration between telecommunications and computing systems in enabling users to access, store, transmit, and manipulate information; it includes, among others, electronics and nanotechnology, optics, telecommunications and remote sensing, computer systems and software engineering, wireless systems, Artificial Intelligence (AI), sensor networks, robotics and automatic control (Murray, 2011). Consequently, nanomaterials for improved food safety, broadband high speed cellular and Internet connectivity, Radio-Frequency Identification (RFId), mobile and wearable sensors, high resolution satellite and airborne-based remote sensing, drones, autonomous farm machinery equipped with sensors and GPS (Global Positioning System) are only some of many applications that ICTs offer to the agri-food industry (Pellegrini and Mozzon, 2018a). ICTs has played a role, mostly in supply chain management but it is increasingly being included in farm management and even into food development itself. Humanity now faces a choice about what sort of food system it will develop and ICTs plays a critical role in that decision. Two main sets of ICTs interventions will become increasingly integrated into the overall food system (Berti and Mulligan, 2015):

1) continued streamlining of the traditional industrialized supply chain through the application of sensors and the creation of new forms of supply chains that augment food products through the use of new technologies;

2) ICTs solutions that allow for a re-territorialization of parts of the food system into local communities through the creation of reliable, secure, and economically sustainable "short" supply chains.

If effectively implemented, the latter group of ICTs interventions can promote the redistribution of productive elements of the economy across regions or nations around the globe. According to the Food and Agriculture Organization (FAO) of the United Nations (UN) and the International Telecommunication Union (ITU) (FAO and ITU, 2017), ICTs are (and will be even more in the next future) present in all aspects of the agri-food sector. The main objective of the present study is to review the state-of-the-art of using ICTs in food technology and to outline how the evolution of these technologies could be useful for the whole agri-food sector.

The present paper aims to analyze how the rapid progress of ICTs occurred in the last decade will impact

Table 1. Comparison between HACCP and HARPC.

Key Comparison Points	HACCP	HARPC
Is the preventative approach based on a standard, guideline or a set of laws?	Based on a guideline recommended by CODEX and National Advisory Committee on Microbiological Criteria for Foods	Based on the Food Safety Modernization act (FSMA) and principally, the final rule for Preventive Controls for Human Food
What food safety risks are considered using the preventative approach?	Conventional -Biological, Chemical and Physical	Beyond the conventional risks for actual and potential food safety hazards
What is the goal of the preventative approach?	To prevent, eliminate (or) reduce hazards to a safe level (in that priority)	Preventive controls that prevent or significantly minimize “known or reasonably foreseeable” risks
Who is the primarily responsible for the development and maintenance o the preventive plan?	Primarily, a competent HACCP coordinator with assistance from multidisciplinary team	Trained Preventive Controls Qualified Individual as described in FSMA
At what frequency is the preventive plan being reviewed by the facility?	At least once a year, or when required	At least once in 3 years, or when required
The pan is mandatory or what type of establishments?	For the U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) mandated establishments, or when required for certification purposes	For all establishments along the food supply chain that serve U.S. consumers, unless exempted
The plan is excluded or exempted or what type of establishments?	Unless mandated or required for certification, HACCP is voluntary, and Good Manufacturing Practices (GMPs) are mandatory	Exemption list is provided by FDA, but this does not exempt facilities from following at least Current GMPs
Who is the interested party here? For whom is the plan for?	Stakeholders: auditors, inspectors and customers	FDA
What is the documented approach for making the preventive plan?	12 Steps of HACCP (includes 7 Principles)	7 Steps of Developing a HARPC Plan

Source: https://www.foodsafetymagazine.com/enewsletter/haccp-vs-harpc-a-comparison.

the agri-food sector. The study first involved a review of the main food laws and regulations adopted worldwide and then a review of the state-of-the-art of ICTs used in the food sector. Ninety-nine of laws, regulations, scientific papers and online publications covering the last ten years, from 2009 to 2019, have been used for the present study.

THE REGULATORY LANDSCAPE OF FOOD SAFETY

A summary of the worldwide regulatory landscape of food safety is given.

United States

About 48 million people in the U.S. (1 in 6) get sick, 128000 are hospitalized, and 3000 die each year from foodborne diseases (Centers for Disease Control and Prevention, 2016). This is a significant public health burden that is largely preventable, and a threat to the economic well-being of the food system. The Food and Drug Administration (FDA) Food Safety Modernization Act (FSMA), signed into Law in 2011, is transforming the food safety system by shifting the focus from responding to foodborne illness (reactive approach) to preventing it (proactive approach) (Food and Drug Administration, 2013). The essence of FSMA proposed rules is then prevention. Under the FSMA, the FDA has now a legislative mandate to require comprehensive, science-based preventive controls across the food supply chain. As per final rule of FSMA released on November 2015, this means that food facilities subject to FSMA (all the U.S. Companies dealing with food processing, packing or storage and those selling into the U.S. market) must conduct Hazard Analysis and Risk-Based Preventive Controls (HARPC) and shall establish preventive control measures to reduce the risk of food contamination (Safe Food Alliance, 2019). Hazard Analysis and Critical Control Point (HACCP) and current Good Manufacturing Practices (cGMP) are essentially designed to ensure that food is manufactured, processed, packaged and stored in sanitary conditions to prevent post-process contamination. Although the HACCP and HARPC plans have similar concepts and goals, the approach of HARPC is different from HACCP, as the former enforce preventive controls in order to identify potential risks or threats to the food supply and to implement appropriate corrective actions proactively to prevent contamination. Science-based standards for conducting a hazard analysis, and implementing and documenting preventive controls are being defined by the FDA. In Table 1 a comparison between HACCP and HARPC is reported. HARPC cover food safety concerns beyond CCPs; instead of only looking at process steps where controls can be applied (as in HACCP plans), HARPC relies on the applicable FDA regulations, standards, and guidance documents to develop a preventive controls plan. HARPC can be therefore seen as an upgrade to HACCP, a global standard conceptualized in the 1960s (Maloy, 2015). In the transition from HACCP plan to HARPC plan, the goal is to keep existing critical control points in the food safety plan while supplementing it with prerequisite programs, practices and procedures to effectively control hazards in a more layered framework that traditionally occurs in a HACCP system. Food

Table 2. Scheme of main initiatives intended to enhance the EU control system as a whole for detecting and countering frauds in the food chain.

Current initiatives	
Name of the initiative	**Details**
The European Food Fraud Network & EU Coordinated Cases	
The AAC (Administrative Assistance and Cooperation System)	
EU-wide Coordinated Control Plans	Plans on horse meat (2013), fish (2015) and honey (2015)
Training for Food Fraud	Five specific workshops per year on eCommerce and Investigation Techniques.
New Legislation on Official Controls (OCR)	EU Reference Centers for food authenticity, stronger sanctions and broader scope for food fraud.

Source: https://www.foodstandards.gov.scot/downloads/Eric_Marin_Presentation.pdf.

facilities subject to FSMA rules are responsible for (a)understanding potential risks and developing science-based measures to control those risks before a problem actually occurs and (b) verifying that their suppliers are providing them with safe materials and ingredients; as a consequence increased importance is being placed on monitoring, record keeping, traceability and verification (Food and Drug Administration, 2013).

European Union (EU)

European Food Safety Authority (EFSA) is a European agency funded by the European Union that operates independently of the European legislative and executive institutions (Commission, Council, Parliament) and EU Member States (European Food Safety Authority, 2015). EFSA was set up in 2002 following a series of food crises in the late 1990s to be a source of scientific advice and communication on risks associated with the food chain. The agency was legally established by the EU under the General Food Law - Regulation 178/2002.

The General Food Law created a European food safety system in which responsibility for risk assessment and for risk management are kept separate; EFSA is responsible for the former area, and also has a duty to communicate its scientific findings to the public (European Food Safety Authority, 2015). As the risk assessor, EFSA provides scientific opinions and advice, among others, nutrition and food safety; such advice contribute to form the basis for European policies and legislation. Moreover, through environmental risk assessments, EFSA takes into account the possible impact of the food chain on the biodiversity of plant and animal habitats (European Food Safety Authority, 2015). The General Food Law sets out an overarching and coherent framework for the development of food and feeds legislation both at Union and national levels. To this end, it lays down general principles, requirements and procedures that underpin decision making in matters of food and feed safety, covering all sectors of the food chain, including feed production, primary production, food processing, storage, transport and retail sale. Moreover, it creates the main procedures and tools for the management of emergencies and crises as well as the Rapid Alert System for Food and Feed (RASFF) (European Commission, 2018). The General Food Law Regulation ensures a high level of protection of human life and consumers' interests in relation to food, while ensuring the effective functioning of the internal market; in particular, it defines the general requirements for food safety (article 14), traceability (article 18) and import/export of food and feed into/from the European Community (articles 11 and 12). Particular attention was also placed to responsibilities: article 17 imposes on food business operators an obligation according to which they must actively participate in implementing food law requirements by verifying that such requirements are met. This general requirement is closely linked to other mandatory requirements laid down by specific legislation (Food Standards Agency, 2009) (for example, HACCP implementation in the field of food hygiene). Since 2013, the European Commission has started several activities intended to enhance the EU control system as a whole for detecting and countering frauds in the food chain (Marin, 2018); current initiatives, summarized in Table 2, include the European Food Fraud Network, supported by an IT system named Administrative Assistance and Cooperation System (AAC) and EU-wide coordinated control plans.

Australia/New Zealand

Food Standards Australia New Zealand (FSANZ) is a statutory authority in the Australian Government Health portfolio, it develops food standards for Australia and New Zealand (Food Standards Australia and New Zealand, 2019). The Food Standards Code is enforced by state and territory departments, agencies and local councils in Australia; the Ministry for Primary Industries in New Zealand and the Australian Department of Agriculture and Water Resources for food imported into Australia. The standards in the Food Standards Code are legislative instruments under the Legislation Act 2003. In particular, standard 3.2.1 ("Food Safety Programs", latest version registered on December 14, 2018) is based upon the principle that food safety is best ensured through the identification and control of hazards in the production, manufacturing and handling of food as described in the HACCP system, adopted by the joint World Health Organization (WHO)/FAO Codex Alimentarius Commission, rather than relying on end-product standards alone. This standard enables states and territories to require food

businesses to implement a food safety program based upon the HACCP concepts (Food Standards Australia and New Zealand, 2015). Moreover, standard 3.2.2 (“Food Safety Practices and General Requirements”) sets out specific requirements for food businesses and food handlers.
This standard specifies process control requirements to be satisfied at each step of the food handling process. Some requirements relate to the receipt, storage, processing, display, packaging, distribution disposal and recall of food; other requirements relate to the skills and knowledge of food handlers and their supervisors, the health and hygiene of food handlers, and the cleaning, sanitizing, and maintenance of premises and equipment (Food Standards Australia and New Zealand, 2016).

Asia-Pacific Region

The formulation and implementation of food safety laws and regulations in the Asia-Pacific region are fragmented as it is dealt with by different laws and regulations under different ministries and departments; due to this lack of a coordinated approach, food safety issue has come to public attention only on the occasion of food-borne diseases (Prabhakar et al., 2010).
Since there is no single solution for achieving food safety, several well-coordinated efforts are then required at the national, regional and international levels (Prabhakar et al., 2010).

Africa

Food safety-related issues account for almost 2000 fatalities per day on the African continent (Pantucci, 2017). Most African countries rely on subsistence farming but since they are embracing international trade, in recent years such countries are paying a lot more attention to food safety than before; although there have been plans to create a common guideline framework for the countries, many of the existing regulations have no scientific basis (Pantucci, 2017). The African Union (AU) has formulated a promising project that aims to bring participants from different regions to work together toward a common food standards framework (The African Union Commission, 2019).
The project is still in the early stages, focusing on minimizing public health risks and getting consumers to trust the local food system. Main food laws and regulations adopted in Asia, Africa, Latin America and Canada have been collected and made available by the Michigan State University Libraries (https://libguides.lib.msu.edu/c.php?g=212831); this web resource includes a collection of international journals, databases, books and online material about food governance. Around the World, technology has taken over many aspects in day-to-day living but many food safety and quality assurance managers continue to use pen and paper checklists for record-keeping, critical control points monitoring, sanitation schedules and other key legal requirements. As legal requirements are complex, overlapping, and change every couple of years, manual management of HACCP or HARPC plans have now become a resource-intensive and increasingly inefficient process (Food Safety Tech Staff, 2015). Digital food engineering solutions (that is, ICTs solutions) have many benefits for a business such as process improvement and cost savings; indeed, fewer resources are needed to complete food safety inspections and a 60% reduction in time compared to paper-based systems are estimated (Sammon, 2016).

STATE-OF-THE-ART OF USING ICTS IN FOOD ENGINEERING

Efficiency, process control and consumer communications are all closely related to the use of ICTs. Global networks, the internet, networked devices, sensors, and communication intelligence are of foremost relevance for the sustainability of the food sector in meeting its responsibility (Lehmann et al., 2012). The main objective of the present review is pointing out when and how ICTs in food technology can provide added value for food safety and quality management in the supply chain. Several food safety problems occurred worldwide in recent years have heightened consumers’ food safety awareness and have caused public distrust of the increasingly complex and globalized food production and trading system (Setboonsarng et al., 2009). Establishing efficient and reliable food traceability systems is, therefore, becoming critical for the food industry and the public sector, as well as for consumers. International literature supported by case studies show that ICTs can help to establish an efficient traceability system improving consumers’ confidence in the products, both in developed as well as in developing countries; such studies also show that collaboration between public and private sectors is a key to success (Setboonsarng et al., 2009). The key advantage of using ICTs within the supply chain is that they allow for faster transferring, sharing, querying and analysis of digital information. Especially for developing countries, the initial investment in ICTs hardware, software, training, and maintenance can be a considerable cost. However, all indications (Setboonsarng et al., 2009) suggest that transition costs towards ICT-based systems are reduced by the fact that safer systems lower the risks industries face from supply chain accidents.
A safe traceability system can be therefore seen as a worthwhile investment for industries in developing countries that are aiming to compete globally in the long term (Setboonsarng et al., 2009). ICTs now offer an alternative to time-consuming, paper-based food safety inspections and related processes. A new generation of smart wireless sensor-based systems can be used in

refrigerators and other food preparation and holding areas to provide continuous automated 24/7 monitoring and recording of temperature, humidity and door status. RFId is used for supply-chain management and traceability in the food industry to improve, for example, the cold-chain logistics service quality and to maintain food safety standards (Piramuthu and Zhou, 2016). Wireless handheld devices can also be used to collect food temperature and hygiene check data providing real-time non-conformance reports by clicking a button. User-authenticated time-stamped logged data from fixed or handheld sensors can be wirelessly downloaded to a secure Cloud-computing based system which can automatically generate food safety compliance reports, making HACCP/HARPC automation both possible and practical (Nash, 2013). Why is wireless technology important for the food industry? Wireless technology is inherently flexible and scalable from a single local site to multi-site operations, using web-based software for configuring, managing and real-time monitoring the complete network from one location. As wireless technologies are growing, the data rate, mobility and coverage increases (Gupta and Jha, 2015). Just to give an idea of recent technological advancements in wireless technology, today's smartphone provides a typical download speed over 600 times faster than available technologies just 25 years ago (Nirmala et al., 2018). In spite of recent advances in wireless technology, wireless networks continue to be designed as independent networks that make resource decisions without considering co-located networks. In spite of recent advances, wireless technology has its limitations: as an example, wireless networks continue to be designed as independent networks that make resource decisions without considering co-located networks. Wireless networks need thus to cooperate to provide better performances and more robust and reliable services (Martin et al., 2011). Indeed, it is known that cooperating independent wireless networks (such as commercial cellular providers) are able to provide a higher capacity, more robust network that could be provided if each network operated independently; then, several solutions at both the network as well as the radio level have been suggested to support hybrid or heterogeneous networks (Martin et al., 2011). A review of sensors, applications, projects and novel techniques recently used or proposed for the agri-food industry is given.

Contactless Sensors for The Food Sector

Nowadays, measurements of core and surface temperatures are often performed by using, respectively, a waterproof penetration thermometer combined with an integrated infrared (non-contact) sensor. This kind of device can be used everywhere in the food sector (for example, for HACCP or HARPC compliance monitoring). All readings from the two sensors can be automatically and wirelessly sent to a HACCP checking App running on a smartphone, speeding up the monitoring process, saving money and reducing the risk of human error (Testo and KGaA., 2019). Moreover, optical sensor systems are being used in food and beverage business field in order to perform contactless and non-destructive determination of oxygen ingress in food packaging (Kelly et al., 2018); indeed, it is known that oxygen inside packaging can lead to oxidative deterioration of foods or beverages. The amount of tolerable oxygen inside packaging can differ greatly according to the packed product; unwanted oxygen taken up during production or the filling process can shorten the shelf life of certain products (Kelly et al., 2018). Quality is a key concern for the manufacturers in the food processing industry and one of the primary factors influencing the quality of food products is the moisture control of the product as it is being manufactured. In order to maintain consistency of moisture content, real-time moisture measurement and control are currently performed in the food processing manufacturing process by using near-infrared (NIR) reflectance and radio frequency (RF) contactless technologies (Sensortech Systems, 2019).

Robotics and Remote Sensing: The Flourish Project

To feed a growing world population with the given amount of arable land, new methods of sustainable farming that increase yield while minimizing chemical inputs such as fertilizers, herbicides, and pesticides are needed. Precision agriculture seeks to address this challenge by monitoring key indicators of crop health and targeting treatment only to plants or infested areas that need it. Such monitoring is currently a time consuming and expensive activity (ICT-AGRI Secretariat, 2018). The goal of the Flourish project (http://www.flourish-project.eu), funded by the European Community's Horizon 2020 program, is to bridge the gap between the current and desired capabilities of agricultural robots by developing an adaptable robotic solution for precision farming (ICT-AGRI Secretariat, 2018). By combining the aerial survey capabilities of a small autonomous multi-copter unmanned aerial vehicle (UAV) with a multi-purpose agricultural unmanned ground vehicle (UGV), the system will be able to survey a field from the air, perform targeted intervention on the ground, and provide detailed information for decision support, all with minimal user intervention (ICT-AGRI Secretariat, 2018). Precision farming can help increase crop yields, reduce costs, including labour costs, and optimize process inputs (European Commission, 2019).

All of these can help increase profitability. At the same time, precision farming can increase worker safety and reduce the environmental impact of agriculture and farming practices, thus contributing to the sustainability of agricultural production (European Commission, 2019). Solutions for precision agriculture are being investigated with the aim of obtaining a more efficient healthy production with lower chemical inputs; precision agriculture can thus provide a significant contribution for consumers also in terms of food safety and food quality

(European Parliament Research Service, 2016; De Baerdemaeker, 2017). According to the FAO, advances in ICT are leading to improvements in food security and safety in Asia and the Pacific (Food Navigator-Asia, 2016); in particular, the use of ICTs will help rationalize resources (both financial and human) while generating new revenue streams and improve the livelihoods of the rural community. From drones to smartphones, while providing technologies and practices, ICT is also making such technologies more affordable and applicable for even the poorest smallholder and family farmer (Food Navigator-Asia, 2016).

The precision agriculture industry, and robotics in particular (Owen-Hill, 2017), is expected to be worth 7.87 billion USD by the year 2022 (Salgarkar, 2018); agricultural drones alone are predicted to be worth 3.9 billion USD by the same year (MarketWatch, 2016). The value of the global food automation industry is expected to double in the next five years, reaching 2.5 billion USD by 2022 (Rousseau, 2017). The Asia-Pacific market represents a huge driver due to the popularity of ready-to-eat foods in that part of the world (Owen-Hill, 2017). Of the world's population, 50% lives in rural areas, but in Africa, this figure is closer to 70% (Ponelis and Holmner, 2015). Although there are significant migration and rapid urbanization, rural development remains a firm development goal (Heeks, 2014). As part of the Innovation in Outcome Measurement (IOM) initiative (TechnoServe, 2018), which was a two year program launched in 2015 by the Bill and Melinda Gates Foundation and TechnoServe to develop and test cheaper, better, and faster ways of collecting agricultural data, a pilot project has been conducted in Uganda to demonstrate the business case for providing drone services to African farmers (FAO, 2018). This case study showed that the use of drones can reduce farming infrastructure and inputs costs.

Microbial Testing in Drinking Water Via AI

In the framework of HARPC, a food facility subject to FSMA has to draw up a verification program including microbial testing and testing of water quality (Safe Food Alliance, 2018). Time-consuming laboratory tests and indirect measurements are examples of methods being used today to monitor microbial drinking water quality. Results obtained by such methods are either delayed or insufficient to support proactive action required by HARPC rules (Højris et al., 2016). An optical on-line bacteria sensor with a 10 min time resolution has been developed (Højris et al., 2016). The sensor is based on 3D image recognition. Each suspension scan includes 59 measured parameter values to characterize the specific particle types. Neural networks, a form of AI, are used to establish a boundary between bacteria and abiotic particles in the 59-dimensional space spanned by these parameters. The result of the research has been an algorithm capable of distinguishing and quantifying bacteria (*Bacillus subtilis*, *Lactococcus lactis*, *Escherichia coli* and *Vibrio natriegens*) and abiotic particles in pure and mixed suspensions with a certainty of 90 ± 7% for monotype suspensions and 78 ± 14% for mixed-type suspensions. The sensor reports correct particle sizes in the range of 0.77–3 μm; smaller abiotic particles or bacteria may not be detected or classified correctly. The proposed technology can monitor changes in the concentration of bacteria so it is well suited for rapid detection of critical conditions such as pollution events in drinking water (Højris et al., 2016).

Neural Networks to Retrieve A Recipe from A Collection of Test Recipes and Images

The image to recipe retrieval (im2recipe) developed at Massachusetts Institute of Technology (MIT) (Salvador et al., 2017), represents another example of how AI can be usefully applied in the food sector in its widest sense. In the paper, authors presented the large-scale Recipe1M dataset, the largest publicly available collection of recipe data; it contains over one million structured cooking recipes with associated images. The contents of the dataset are grouped into two layers. The first is provided as free text and contains a list of ingredients and a recipe as a sequence of instructions for preparing the dish. The second layer is built upon the first and includes any RGB (Red, Green and Blue) images in compressed JPEG (Joint Photographic Experts Group) format with which the recipe is associated. Additionally, a subset of recipes are marked down with course labels (for example, appetizer, main course, beverage) (Salvador et al., 2017). Using the Recipe1M dataset, authors trained an Artificial Neural Network (ANN) to find a joint embedding (a set of algorithms defined in model theory and universal algebra) of recipes (that is, ingredients and instructions) and images. Given a food image, the task of im2recipe retrieval was then to retrieve its recipe from a collection of test recipes. The method yields impressive results on an image-recipe retrieval task, even when compared with human performance on the im2recipe task (Salvador et al., 2017). Such a tool can go beyond applications in culinary arts. Given the abundance of online recipe collections with food images shared by users on social media, it may also allow getting an insight into the preparation of food helping public health agencies in their role of surveillance of human infectious disease. There are many other examples of how ANNs and machine learning can be profitably applied in food industry. When the data explosion (the so-called Big Data) in modern food processing research requires sophisticated analysis methods to uncover the hidden causal relationships between single or multiple responses and a large set of properties, ANN is one of the most versatile tools to meet the demand (Chen et al., 2011). A recent review (Correa et al., 2018) reported several applications of ANNs in the food industry such as:

a. Prediction of bioactive compounds and physicochemical characteristics. Artificial intelligence

b. algorithms have been used, among others, to predict the determination of antioxidant activity of essential oils and the determination of linoleic acid, to predict optimal conditions of 15 properties of the bean *L. Viciafaba* (length, width, thickness, arithmetic and geometric diameter, sphericity index, image area, gravity, weight, real density, apparent density, volume, porosity, stability of fill angle and emptying) depending on the moisture content, and for determining the fermentation rate of cocoa beans based on color changes through measurements of free amino acids (these parameters were evaluated by experimental values and compared with the proposed model, showing that there was no statistical difference between them);

c. Determination of shelf life and maturity stages. The optimum cold storage temperature of cooked rice was predicted through the utilization of ANNs; the model was found to require a storage temperature below -25°C and microwave heating below -15°C to maintain the acceptability of the samples for more than 40 days; ANNs were also used for the prediction of maturation time and the variation of milk mixtures (cow, sheep and goat) for cheese making, using the content of 19 fatty acids and NIR spectral values as input data;

d. Prediction of food quality. In order to improve quality characteristics in food products, artificial intelligence was used to predict the number of coliform bacteria and *E. Coli* present in tomato (*Solanum lycopersicum*) and lettuce leaves (*Lactuca sativa*) after carrying out a disinfection process with hypochlorous and peracetic acid;

e. Prediction and parameters optimization with Response Surface Methodology (RSM). The influence of temperature, thickness and type of pretreatment, color and texture during vacuum dehydration of banana has been evaluated by comparing the response surface and an ANN for the prediction of the mentioned parameters; it was found that the proposed ANN model obtained better predictions for the values of rehydration rate, sweep rate, color and texture, than the model proposed by the RSM;

f. Thermal treatments. ANN model was used in order to model the heat and mass transfer kinetics, drying characteristics, approximating the moisture content and quality of apple tissue; ANN models were also developed for predicting physicochemical properties of apple tissue during hot air drying in thin layer (Winiczenko et al., 2018). When compared to conventional Multivariate Linear Regression (MLR), an ANN-based model is indeed recognized as a valid tool for dynamics modeling because it does not require parameters of physical models, has an ability to learn the solution of problems from a set of experimental data, and is capable to handle complex systems with nonlinearities and interactions between decision variables (Curcic et al., 2013).

Blockchain Technology for The Food Industry

Last but not least, Blockchain technology must be mentioned in the present review about ICTs applied in the food industry. Blockchain technology first got noticed for supporting Bitcoin and other cryptocurrencies with its secure, transparent, and decentralized design for record-keeping and nowadays it seems it is going to change the world (Pretz, 2018a). Although most blockchain applications have been devoted to cryptocurrency exchange, the framework can theoretically be applied to any scenario requiring assured/verified information in order to improve its operations (The Economist, 2015). Blockchain involves a database that records every transaction and makes it visible to all participants with access to the network; moreover, each transaction is blocked by the following transaction, making it almost impossible to delete or edit previous records in the database (Rozenfeld, 2018). A blockchain system uses cryptology in order to assure security and trust (Institute of Food Technologists, 2018). The World Health Organization estimates that almost 1 in 10 people become ill every year from eating contaminated food, with 420000 dying as a result (World Health Organization, 2015). As an example, an *E. coli* outbreak in the United States began in April 2018 (the largest in more than a decade) came from tainted romaine lettuce that sickened more than 200 people in 36 states; it took government investigators two months to track the lettuce back to a grower in Yuma, Arizona (Pretz, 2018a). Global food supply has grown so complex that it has become almost impossible for food producers and retailers to guarantee the provenance of their products (Crossey, 2018).

In the food and beverage supply chain, blockchain technology makes food traceability possible, tracking products to their source for enhanced food authenticity and safety (Detwiler, 2018). The use of blockchain for the food industry brings huge advantages for every actor within the supply chain (Crossey, 2018): for food producers, any attempts to tamper with a food item as it moves through the supply chain can be immediately identified and prevented before the food ever reaches the retailer; for retailers, if a potentially hazardous food product somehow makes it onto shelves, stores can identify and remove only the offending items, eliminating the need for costly batch recalls; finally for consumers, the blockchain offers the transparency and openness needed to reassure them that the food they eat is exactly what the label says it is (Crossey, 2018). Through the use of a simple QR (Quick Response) code (Tiwari, 2016) and a smartphone, customers have the ability to identify properties of food by scanning a package at the point of sale and receive a full and complete history of foods' journey from farm to fork (Informamuse, 2018; Rozenfeld, 2018). This is particularly useful in areas of food traceability, such as country of origin labeling.

FUTURE TRENDS OF ICTS IN THE AGRI-FOOD INDUSTRY

The food sector, as many other manufacturing sectors, must meet the increasingly compelling needs arising from national and international standards and from the market requirements in terms of quality, safety, security, traceability and carbon footprint. This requires an ever-increasing use of robotics and automation systems (Paoli and Swainson, 2018). Robotics and automation can, therefore, play a significant role in society meeting 2050 agricultural production needs (IEEE, 2012). Using automation in food processing has many benefits: robots can achieve consistent results more quickly than human employees can; health and food safety issues are also less of a problem with robots that can be designed to handle extreme conditions such as high temperatures; especially in repetitive processes, robots can help lower the cost of production by producing higher yields with no need for training or breaks (Chrisandina, 2018). It is also known (Bunte et al., 2009) that food supply chain networks (FSCN) have become a part of the knowledge economy; FSCN is developing into open networks sharing information since open networks offer many opportunities for generating value added.

In the present paper, the term information is related to both data and knowledge, as data is meaningful information representing values attributed to parameters, and knowledge signifies understanding of a concept (Merriam-Webster, 2019). However, two are the main bottlenecks in the knowledge economy: most of the huge amount of data collected by food companies is not used at all and such companies are not ready to process all data available. The most important challenge the food economy faces refer to getting managers, employees and the models they work with ready for the knowledge economy (Bunte et al., 2009). How ICTs are expected to evolve and how they could further improve the level of safety and automation for the food industry. In particular, we focus our attention on the integration between Blockchain and the Internet of Things (IoT), 5G (the next generation of wireless communication networks), Big Data analytics and computing/processing systems.

Promising Blockchain Applications in Agri-Food Sector

The Institute of Electrical and Electronics Engineers (IEEE) with its Standards Association working group and several other organizations are exploring how blockchain technology could track the source of a foodborne outbreak and help contain it. Rather than each company storing information in its own system, the businesses would contribute encrypted blocks of data to a distributed ledger that could be monitored and verified (Pretz, 2018a). Monitoring fish supply is just an example of future applications of blockchain: since it is known (Rozenfeld, 2018) that 20 to 30% of the seafood sold in the United States is caught illegally, blockchain technology could help ensure that the fishing industry is legally compliant, letting the food industry know where fish were caught and by whom. In other words, a blockchain system would allow everyone involved in the supply chain, including those who sell fishing supplies, fishing companies, fishmongers, and customers, to have access to that information (Rozenfeld, 2018). The increasing interest of IEEE in the agri-food sector is also witnessed by the “Blockchain-2019” conference that will be held in July 2019 in Atlanta, USA (Institute of Electrical and Electronics Engineers, 2019): since blockchain technology is expected to play an important role in secure decentralization, participants at the conference will discuss about blockchain in agriculture, as well as blockchain in supply chain management, in connected and autonomous vehicles, in the IoT, in next-generation wireless communications and in cyber-physical systems (Institute of Electrical and Electronics Engineers, 2019).

The IoT and Machine-To-Machine Market for The Agri-Food Sector

The IoT is the network of physical devices (for example, sensors and actuators), vehicles, home appliances and other
items embedded with electronics, software and connecti vity enabling such “things” to connect and exchange data (International Telecommunication Union, 2015). Each thing in the IoT is uniquely identifiable and is able to inter-operate within the existing Internet infrastructure; the IoT can be thus seen as a network of connected services provided by a myriad of electronic objects that interact with each other via machine-to-machine (M2M) communications (International Telecommunication Union, 2012). The M2M market is expected to be very broad (Beecham Research Limited, 2017) and the industry is one of the many sectors that will certainly be affected by IoT development. With regard to the agri-food sector, resource automation in agriculture and irrigation, assembly and packaging, management of supply chain infrastructure and distribution are some examples of factory processes that will benefit from the IoT. The number of connected devices is destined to grow worldwide, going from the current 30 billion to more than 60 billion in 2025 (Statista, 2019). So many connected devices will generate Big Data and related challenges. Current wireless technologies are not able to support such a high amount of traffic then connectivity is the only hurdle that could, in some way, slow down the exponential diffusion of IoT devices (Marchetti, 2015).

The Next Generation of Wireless Network Technology for Agriculture and Food-Related Applications

The fifth generation (5G, see https://5g.ieee.org) of wireless network technology will deliver data with less than 1 ms of delay (compared to about 70 ms on today’s 4G networks) and bring to users peak download speeds of 20 Gb/s (compared to 1 Gb/s on 4G); moreover, 5G is expected to support the connection of many more devices handling much more mobile data (1000 times the current wireless capacity). It is expected that in the next future 5G will impact a wide range of industries and agriculture is one of them (CB Insights Research, 2019). Besides IoT, some future applications that will require 5G are industrial automation for the food sector (Ludwig et al., 2018), autonomous vehicles for the food supply chain (Heard et al., 2018) and vehicles for future robotic agriculture systems (UK-RAS Network, 2018). It is important to note that agriculture industry will have to wait longer than most industries to reap the benefits of 5G, as 5G networks will largely be deployed in urban areas first (CB Insights Research, 2019). According to a recent study quantifying the effectiveness of the spatial and temporal rollout of 5G in Britain, rural area coverage will take place between 2024 and 2030 (Oughton and Frias, 2018). Meanwhile, however, the integration of future and existing spectrum will play a major role in lowering the costs of a network rollout capable of proving 10 Mbps per rural user, which is comparable to the UK's current fixed broadband Universal Service Obligation (USO) (Oughton and Frias, 2018).

A 5G-ready phone’s costs in 2019 will likely be 40-50 USD higher than for a comparable 4G phone (Stewart and Lee, 2018) but by 2023, as 5G smart-phone prices continue to fall making it more affordable to the majority of people, 5G handset sales are expected to reach the hundreds of millions (TelecomLead, 2018).

From Cloud to Fog Computing for Logistics and Food Traceability Applications

In the context of Big Data, Cloud computing is evolving towards the Edge computing, that is, a “fog” of very powerful terminals (smartphones) at the edge of the network. Although Fog and Cloud use the same resources (networking, computer, and storage) and share many of the same mechanisms and attributes (machine virtualization software), Fog computing serves as a computing layer that sits between the edge devices and the cloud computing (Bonomi and Milito, 2012). Applications that make use of the Fog can avoid the network performance limitation of Cloud computing while being less resource constrained than edge computing. Fog computing can represent the appropriate platform for a number of critical IoT services and applications, for example, logistics and food traceability systems (Mededjel et al., 2017). In recent years, the increase in commercial traffic, specifically in the food industry, is having a negative impact on the environment and the costs of logistics and also an increased risk on quality, safety and food traceability. Food traceability systems based on IoT technologies and Fog computing to collect information and record events related to products anywhere in the supply chain are therefore being developed with the goal of satisfying users’ requests in terms of quality and safety of their products (Mededjel et al., 2017).

From Machine-To-Machine to Device-To-Device

In 5G networks, Device-to-Device (D2D) communication is expected to be a vital part in the development of the IoT. The D2D communication allows user equipment to communicate with each other, with or without routing network infrastructures such as an access point or base stations (Shaikh and Wismuller, 2017). Future applications of D2D communications include short-range telemetry, logistic services and supply chain management. As an example, a solution for real-time data collection is represented by a Bluetooth-enabled device: such small and lightweight devices can be powered by a simple battery for many years; by means of built-in sensors, the device is able to measure, for example, the temperature and humidity or other environmental parameters important for sellers or growers and send this information to a smartphone or to another Bluetooth-enabled device connected to the Internet (Pongnumkul et al., 2015). Besides Bluetooth and Bluetooth low energy (Bluetooth LE), a number of other wireless connectivity protocols (including ZigBee, Wi-Fi, Z-wave, 6LowPAN, etc.) can be used in IoT application domains such as smart agriculture and smart farming (Kazeem et al., 2017); the choice regarding which is the most efficient wireless connectivity standard to choose for a given application domain is based on many parameters like data rate, network range, power consumption, type of environment and devices, network topology, cost, etc (Kazeem et al., 2017).

Other Trends in Icts For Future Applications in Agri-Food Sector

The U.S. Intelligence is working to develop a portable laser scanner that can identify trace amounts of any one of 500 chemicals spanning the dangerous (the highly explosive Pentaerythritol tetranitrate, PETN) to the mundane (caffeine) on surfaces from a distance of 5 to 30 meters (Moore, 2018). The key objective of the laser scanner is to provide high-resolution infrared (IR) spectra enabling to identify target chemicals at mission-relevant concentrations in the field with real-world clutter and background. As IR spectroscopy is currently one of the most common spectroscopic techniques used in the food industry (Sun, 2009), food safety monitoring will benefit from future developments and applications of this kind of sensor. Vintners in California valleys are facing two shortages: water and workers. The University of California is partnering with grape growers on a high-tech solution: The Robot-Assisted Precision Irrigation Delivery (RAPID) system (Pretz, 2018b). Such a system is expected to be more efficient and with less human intervention. Growing grapes is indeed a tricky business. Their quality depends in part on how much water is absorbed by the vines’ roots. Current drip-irrigation systems can’t be adjusted and some grapes end up with too much water, some with too little. The aim of the RAPID system is to reduce water use by turning each watering pipe into a precision irrigation system while preserving the quality of the grapes (Pretz, 2018b).

RAPID project is only one of the many agricultural technology projects in which IEEE members are involved with. The main theme of recent IEEE “IoT Vertical and Topical Summit on Agriculture”, held in Tuscany (Italy) on May 2018, was the “Digital Revolution - Farming 4.0!” and it aimed to explore the application of IoT solutions in the agriculture industry: from growth to processing, to distribution, retailing, and consumption of food products. As an example, the IEEE *SmartAg Initiative* aims at creating a platform that connects researchers, practitioners, and policy makers to facilitate the development and application of existing and emerging smart technologies to enhance global agri-food systems (Verboncoeur, 2018). SmartAg technologies include, among others, hyperspectral sensing (visual, lidar and microwave), machine vision, sensors for volatile organics, autonomous *farmbots* and UAVs, seed treatment, animal health monitoring, food sterilization (plasma and UV), smart packaging and food supply chain traceability via blockchain (Verboncoeur, 2018).

Ever-Developing Technology Towards 2030

IEEE Communications Society is now promoting a brainstorming between research communities both in academia and industry to predict the use cases and new scenarios, to determine the technical requirements, and to develop the enabling technologies, protocols, and network architectures towards the standardization of beyond-5G wireless networks. As stated in a recent report (Basin et al., 2018), despite 5G improves on data protections offered in 3G and 4G standards, in its current state it will not close all the security gaps. It is therefore important for the food and beverage industry actors to participate in the phase of 6G development in order to carry on their needs and expectations in terms of data security, sharing and property.

CONCLUSION

Interest stimulated by the UN 2030 Agenda provides many business opportunities for both telecommunications and food industries. A wide range of industrial IoT applications will be developed in the next future by leveraging the growing ubiquity of wireless and RFID, mobile and sensor devices. The IoT and cloud computing are bringing new approaches to collect, transfer, store and share information through improved cooperation between logistics actors. The development of IoT-based traceability systems will permit to reduce logistical risks in the food supply chains. However, IoT is a complicated heterogeneous network platform so future efforts are needed to address research challenges such as interoperability and standardization. As the food industry will be increasingly interested in ICTs and Big Data, some issues become crucial. First, the access to, and the use and quality of ICTs. There are many factors (policy, legal framework, technology, knowledge, markets, research, etc.) to be considered when addressing food security, but in all of them, ICTs can act as catalysts. As increased access to and use of ICTs can be beneficial to farmers, agricultural industry and food security, managing authorities and international institutions such as EU and ITU are promoting the use of ICTs. Nonetheless, efforts to date to employ these tools have not been uniform or sufficiently widespread. Future efforts for ICTs in the agri-food sector should focus on the following questions: how will the accessibility and affordability of ICTs be? How can ICTs be made transparent to all stakeholders? Will ICTs make data sharing easier or more complicated than it is today? Then, the management and use of data: as it is still up to the operator and the user’s knowledge and experience for actual decision making, who will interpret the data and be responsible for decision-making in the future? Next, linked to Big Data and technological advances in general, the following issues arise: will other or new professional profiles be needed in the food industry in order to handle ICT solutions? Will it be necessary to change the educational programs of food technology engineers and food scientists? Lastly, it becomes crucial to define who owns data and under which conditions data can be shared in particular if sharing is needed between governments and food industries or between food business competitors. These are some of the issues that will need to be considered in the near future.

Furthermore, in the medium- to long-term, investments related to ICTs in the agri-food sector should be focused on service-oriented architecture (SOA)-based IoT solutions. This is justified by the fact that service-orientation software design is based on services that are provided to the other elements of the architecture via applications components, independently of any vendor, product or communication technology. Service-oriented programming represents the latest technological evolution dealing with the drawbacks of objected-oriented programming (for example, communications between two or more applications are not permitted in objected-oriented programming, particularly when applications have been written using different programming languages). Service reusability, greater reliability, improved scalability and platform independence are some of the main advantages of adopting SOA. On the other hand, SOA is not recommended for applications based on technologies of a single vendor, real-time or stand-alone non-distributed applications. Since there are no industry standards or specific technologies relating to the exact composition of an SOA, it can, therefore, be implemented using a wide range of new or existing ICTs. By embracing an SOA approach, even companies coming from developing countries who want to participate in emerging markets can then effectively benefit from software solutions that fit the cost profiles for those countries.

FUTURE EFFORTS AND RECOMMENDATIONS

Future efforts for ICTs in the agri-food sector should focus on the following questions: how will the accessibility and affordability of ICTs be? How can ICTs be made transparent to all stakeholders? Will ICTs make data sharing easier or more complicated than it is today? In the framework of 5G, the Internet of Things is seen as a complicated heterogeneous network platform so future efforts are needed to address research challenges such as interoperability and standardization. Moreover, since there are no industry standards or specific technologies relating to the exact composition of a service-oriented architecture, it can, therefore, be implemented using a wide range of new or existing ICTs. By embracing an SOA approach, even companies coming from developing countries who want to participate in emerging markets can then effectively benefit from software solutions that fit the cost profiles for those countries. It is therefore important for the food and beverage industry actors to participate in the phase of Sixth Generation Mobile Technology (6G) development in order to carry on their needs and expectations in terms of data security, sharing, and property.

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