



Digitalization in the meat chain

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ABSTRACT

The meat supply chain should be regularly monitored to ensure the safety of products. Recent developments in Artificial Intelligence, Internet of Things and blockchain technologies will have a tremendous and disruptive effect on the meat supply chain system in terms of improving the monitoring and surveillance of hazards at multiple points along the meat chain (pre-harvest, harvest, post-harvest), in the farm-to-retail continuum, as well as providing better quality of information to consumers for informed decisions regarding food purchase. The farm-to-fork food chain continuum should be managed to provide an appropriate level of consumer protection (ALOP). This can be achieved by science-based risk assessment, which includes information about the prevalence and concentration of major public health hazards (epidemiological indicators) of zoonotic origin (*Salmonella*, *Campylobacter*, *Listeria monocytogenes*, *Yersinia*, Shiga toxin-producing *Escherichia coli*/STEC) in all modules along the food (meat) chain: farm – transport – slaughterhouse – meat processing – distribution – retail – consumers. The integration of digital technologies to the Food (Meat) Safety Management System or Meat Safety Assurance System will enhance the integration of Food Chain Information and Harmonized Epidemiological Indicators along the meat chain, from farm to retail (bottom-up) and vice versa from retail to farm (top-down). Meat chain digitalization will also increase the transparency and visibility of all actors involved in meat production, processing, distribution and retail (farmers, meat business operators, competent authorities, retailers), and provide the basis for benchmarking producers and retail chains, as well as pro-active consumer participation in defining future food policies at the national and global level.

Keywords: meat chain, meat safety, digitalization, internet of things, blockchain, artificial intelligence.

ИЗВОД

Мониторинг ланца снабдевања месом треба да се регуларно спроводи у циљу осигурања безбедности производа. Недавни развој вештачке интелигенције, интернет ствари и блокчејн технологија имаће изванредан ефекат на систем производње и снабдевања месом у смислу унапређења мониторинга и надзора над опасностима у свим тачкама дуж ланца меса (примарна производња, клање/обрада и прерада/дистрибуција/малопродаја), у континууму фарма–малопродаја, као и обезбеђења бољег квалитета информација ка потрошачима за доношење информисаних одлука када је у питању куповина хране. Континуумом ланца хране „од фарме до виљушке“ треба да буде управљано тако да се омогући одговарајући ниво заштите потрошача. То може да буде постигнуто научно базираном оценом ризика, што обухвата информације о преваленци и концентрацији главних опасности од значаја за јавно здравље (епидемиолошки индикатори) зооноског порекла (*Salmonella*, *Campylobacter*, *Listeria monocytogenes*, *Yersinia*, шигатоксин-продукујућа *Escherichia coli*/STEC) у свим модулима дуж ланца хране (меса): фарма – транспорт – клиника – прерада меса – дистрибуција – малопродаја – потрошачи. Интеграција дигиталних технологија у систем управљања безбедности хране или систем за осигурање безбедности меса омогућиће бољу синтезу информација из ланца хране и хармонизованих епидемиолошких индикатора дуж ланца меса, од фарме до малопродаје (од дна ка врху) и обрнуто, од малопродаје до фарме (од врха ка дну). Дигитализација ланца меса ће такође повећати транспарентност и видљивост свих актера укључених у производњу, прераду, дистрибуцију и малопродају (фармера, субјеката у пословању храном, надлежних државних органа, малопродајних система) и поставити основу за међусобно упоређивање квалитета произвођача и малопродајних ланаца, као и проактивно учешће потрошача у дефинисању будуће политике у храни на националном и глобалном нивоу.

Кључне речи: ланац меса, безбедност меса, дигитализација, интернет ствари, блокчејн, вештачка интелигенција.

1. Introduction

Meat is considered the most valuable livestock product since it is composed of protein and essential amino acids, fat and fatty acids, minerals/microelements (zinc, iron), vitamins (B complex) (Bohrer, 2017; FAO, 2020) and other bioactive compounds with physiological activities (sequences of 2–30 amino acids that have a positive effect on consumer health and an important role in the

prevention of metabolic syndrome diseases and mental illness). The main endogenous bioactive compounds in meat are as follows: conjugated linoleic acid (CLA) (anti-carcinogenic properties), coenzyme Q10 and carnosine (antioxidant and anti-aging effects), taurine (endocrine and immune system stimulation), creatine (improvement of muscle performance), choline (development of the central nervous system), and glutathione (potent detoxifying activity) (Carni Sostenibili, 2020; Vongsawasdi and Noomhorm, 2015).

Meat nutritional value. Meat is food of high nutritional value and in most places in the world the consumption of meat is highly esteemed (McAfee et al., 2010). It is estimated that a relatively small percentage of the world population (2–10%) choose not to consume meat, but rather to use vegetarian and/or vegan-based diet (Corrin and Papadopoulos, 2017). On the other hand, this percentage can still be considered significant on a global level. Therefore, it is important to obtain evidence-based data on the nutritional content and bioavailability of meat-based diets versus vegetarian/vegan-based diets to ensure better evaluation of food choices from the public health level (Sikorski, 1990). Since most non-meat foods contain only 20–60% of the protein density of meat, consideration needs to be made when replacing meat in the diet with non-meat foods. For example, the digestibility index of meat (all animal flesh) is the highest: 1 (100%); followed by cooked beans 0.94, milk 0.93, cooked rice 0.92, eggs 0.91, wheat 0.85, boiled soybean 0.80, corn 0.66, baked potato 0.52 (Ciuris et al., 2019).

Global meat production. World meat production is projected to double by 2050, mostly in developing countries due to the development of their economy and the purchasing power of consumers who demand meat as a protein-rich product (OECD/FAO, 2016). The growing meat market provides a significant opportunity for livestock farmers and meat processors in these countries. It should be taken into consideration that increasing livestock production and the safe processing and marketing of hygienic meat and meat products still represent a big challenge (FAO, 2020). In the meat chain, poultry meat is the primary driver of growth in total meat production when it comes to expanding global demand for this animal protein, which is more affordable than red meats (OECD/FAO, 2016). The main reasons for making poultry the meat of choice are low production costs and low product prices, as well as its multi-confessional dimension (poultry meat is equally accepted and consumed throughout the world by adherents of all major religions – Christians, Muslims, Buddhists, etc.) (OECD/FAO, 2016). In the bovine meat sector, cow herd liquidation occurred in major producing regions, which led to a decrease in beef production in 2015 (OECD/FAO, 2016). Thereafter, beef production stabilized and increased from 2016 onwards, with higher carcass weight neutralizing the decline in cattle slaughter. Pig meat production increased from 2016, mainly driven by China, where herd size stabilized for a while after years of substantial reductions (i.e. a drop of 25 million pigs between 2012 and 2015). After a short period of consolidation of the pork sector, a decrease in pig meat production on a global scale was recorded from August 2018 due to the outbreak of African Swine Fever (ASF) in east Asia, which predominantly affected Chinese pig meat production, where several million pigs were culled in efforts to slow down and stop the spread of the disease (Mason-D'Croz et al., 2020). The sheep meat sector recorded an annual growth rate of 2.1% in the previous decade due to increased production in China, Pakistan, Sudan and Australia (OECD/FAO, 2016).

Global meat safety issues. Meat safety is always at the forefront of public health and socio-economic concerns (Sofos, 2008). Major meat safety challenges are associated with hazards that can be considered

traditional, new or emerging, associated with increased virulence and/or low infectious dose and with resistance to antibiotics or other food related stresses (Sofos, 2008). These hazards enter the meat chain at multiple points along the farm – abattoir – meat processing – distribution – retail – consumer continuum (Nastasijević et al., 2020a). Traditional microbiological/parasitic hazards are *Brucella* spp., *Mycobacterium bovis*, *Bacillus anthracis*, *Trichinella* spp. and *Taenia solium/bovis* (cysticercosis). Emerging hazards are bacterial pathogens such as Shiga toxin-producing *Escherichia coli* (STEC) O157:H7 and non-O157, e.g. the "big six": O26, O45, O103, O111, O121, O145 (USDA FSIS, 2011) or O26, O103, O145, O111, O145 (EFSA, 2020), *Salmonella*, e.g. the "big five": *S. Typhimurium*, *S. Enteritidis*, *S. Infantis*, *S. Virchow*, *S. Hadar* (EFSA/ECDC, 2019), *Campylobacter jejuni*, *Yersinia enterocolitica* and *Toxoplasma gondii*, which are major pathogens affecting the safety of raw meat and poultry, while *Listeria monocytogenes* remains a concern in ready-to-eat (RTE) processed meat products (Nastasijević et al., 2017). Chemical hazards are related to environmental contaminants which may enter the meat chain (mycotoxins, heavy metals, PCBs/Dioxins), veterinary drugs (antibiotics, sulphonamides), hormones and food additives (nitrites, polyphosphates). Other challenges include the need for the development of rapid testing and pathogen detection methodologies with sufficient sensitivity and specificity, traceability systems (blockchain technology), and sensing systems (biosensors). Above all, focus is placed on the agreement and allocation of responsibilities between veterinary and public health authorities regarding monitoring and surveillance systems for zoonotic diseases (including foodborne ones), the establishment of a government policy regarding the maximum allowed contamination level – appropriate level of protection (MACL–ALOP) for food which reaches the consumer (Nastasijević et al., 2020a), as well as the establishment of risk-based food safety objectives in meat production/processing, together with the complete and routine implementation of the risk-based food safety management system, hazard analysis and critical control points (HACCP).

Digitalization in the meat chain. The meat supply chain should be regularly monitored to ensure the safety of products. Healthy animals are an essential precondition for a safe food supply, since zoonotic diseases, including meat borne pathogens, present in meat and, in particular, ready-to-eat meat products are a threat to consumers. Information about livestock health, animal welfare and the prevalence of major meat borne hazards such as *Salmonella*, *Campylobacter*, STEC, *L. monocytogenes*, and *Yersinia* are of utmost importance for effective biosecurity control on farms. For example, early detection of these hazards in fecal samples, and monitoring blood levels of metabolites relevant for animal welfare (hormones) and animal health (acute phase proteins) can provide high-level control in the animal farming industry. For the purposes of meat safety monitoring and control in the meat supply chain continuum, there is a need for the dynamic introduction of digital technologies (Internet of Things (IoT) and development and optimization of point-of-care (PoC) sensing systems (e.g. biosensors) to monitor farm biosecurity and secure Food Chain

Information (FCI) flow in the farm-to-slaughterhouse (F2SC) continuum (bottom-up and top-down).

Namely, in light of the fourth industrial revolution (4S) introducing a new era that builds and extends the impact of digitalization in new and unanticipated ways, there is still an unexplored world of opportunities to foster more effective animal health and welfare control and increase consumer protection via the interface of digital technologies and sensing systems. Therefore, the objectives of this review are as follows: a) to reflect on major challenges in the meat chain in the 21st century related to the fourth industrial revolution, and b) emphasize the need for digitalization along the meat chain to ensure full traceability and early warning systems for the improvement of meat safety, as well as consumer protection and confidence in the food supply chain.

2. Materials and methods

A literature review was performed by analyzing published scientific papers and major sources of information available in scholarly databases such as Web of Science, CAB Direct, national and inter-governmental guidelines. The official web-sites of selected national/international meat chain monitoring and surveillance schemes were also analyzed (e.g. OIE Digital Technologies and Implications for Veterinary Services, FDA New Era of Smarter Food Safety and FAO Digitalization and Innovation to Achieve SDGs). Therefore, this review identified articles (research and review papers, technical reports by international organizations) and databases published in the field of meat safety, zoonotic meat borne pathogens, digital technologies and sensing systems (Precision Livestock Farming) and their application in the meat supply chain, including public health impact. The search string was defined by the following key words: "meat safety", "meat chain", "digitalization", "sensing systems", "biosensors", "animal welfare", "animal health", "meat borne diseases", "fourth industrial revolution". The selection criteria chosen to identify articles that satisfy

the scope and objectives of this review were as follow: 1) focus on meat safety monitoring and surveillance using well-established databases; 2) focus on the potential for the improvement of animal health, animal welfare and meat safety monitoring via digital technologies and sensing systems, and 3) future research. However, some geographical restrictions were applied, by including selected countries with experience in meat supply chain monitoring and surveillance programs using digital technology and sensing systems.

3. Results and discussions

Digitalization of the food (meat) value chain refers to the application of novel technologies, such as sensing systems and Internet of Things (IoT), to enhance the monitoring and surveillance of animal health, animal welfare and food safety aspects throughout the meat chain, e.g. pre-harvest (on-farm), harvest (abattoir), and post-harvest (processing, distribution, retail).

The development of mechanization in the early 19th century, the automation initiated during the 1970s (automated feeding systems, milking robots, manure management), the development of genetics and breeding, and data & information associated with the development of internet from the 1990s and onwards had a significant impact on all aspects of daily activities and manufacture, including food systems (Raheem et al., 2019).

The world's population will reach around 9.1 billion people by 2050 (Figure 1), while food production will increase by 70% to cover additional food demand (UNDESA, 2017). It means that the world population will increase from the current 7.6 billion by around 1.5 billion in the following 30 years. The population in developing countries will reach around 8 billion by that time (49%, 41% and 7% in Africa, Asia and South America, respectively), while the population in the developed world will remain relatively constant, around 1.2 billion, mainly due to steady population growth in the USA (4%) (MSU, 2018).

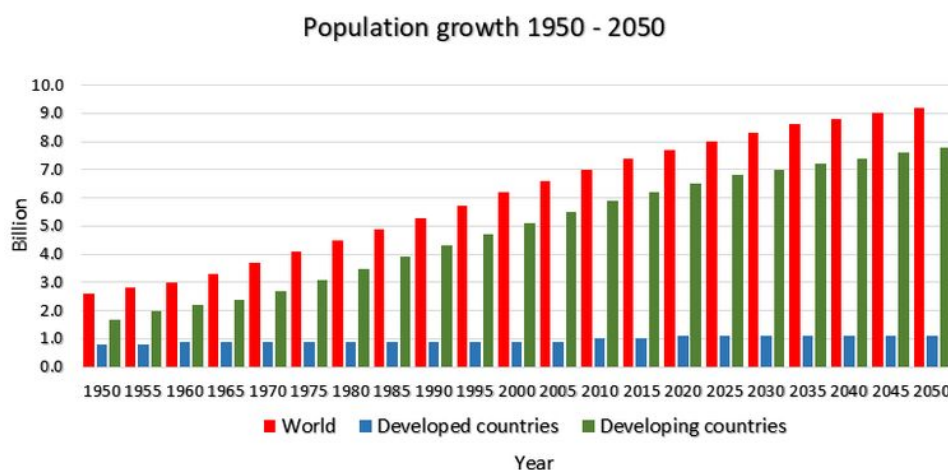


Figure 1. Estimated global population growth between 1950 and 2050 (adapted from MSU, 2018)

On the other hand, global meat production is projected to be 16% higher in 2025 than in the period up to 2015 (OECD/FAO, 2016) and, by 2050, global meat production will increase to 455 million tons (FAO, 2009). The major reason for this total increase in meat

production is attributed to developing countries due to the development of their economy and the purchasing power of consumers who demand meat as a protein-rich product. Poultry meat is the primary driver of growth in total meat production in response to the

expanding global demand for this animal product, which is more affordable than red meats (OECD/FAO, 2016).

To address the above mentioned challenges associated with increasing food demand due to rapid global population growth and to achieve the United Nations Sustainable Development Goals (SDGs), technological innovations, such as digitalization, will have to play an essential role in transforming agri-food systems, including the meat chain.

Advanced digitalization technology can help modern farms optimize economic contribution per animal/flock, reduce the use of antimicrobials, and improve overall animal health and welfare, thus providing the foundation for safe, good quality meat (Neethirajan et al., 2018; Neethirajan and Kemp, 2021).

3.1. Digital technologies in meat chain monitoring and surveillance

The introduction of digitalization into monitoring and surveillance throughout the meat chain, from farm-to-retail, will certainly have a profound and disruptive impact on how farming and animal health systems are managed, including the operation of veterinary services (El Idrisi et al., 2021). These technologies rely on data based on advanced IoT and sensing systems technologies, such as (i) wireless, mobile, point-of-care technologies (biosensors) for animal health and welfare monitoring, disease surveillance, animal reproduction and behavior, reporting and information sharing, (ii) advanced data processing technologies (big data, algorithms) for early warning and uncovering of hidden patterns, predictions and correlation with animal health and welfare, and (iii) blockchain application for effective management of different inputs originating from biosensors.

The implementation of digital technologies will improve livestock health and productivity, reduce animal diseases, ensure the high quality and safety of meat, thus reducing public health risks via the environment-animal-human interface (One Health approach). In addition, the adoption and utilization of novel technologies will also make an influential contribution through solutions in tackling global challenges such as food security, global health, antimicrobial resistance, climate change, reduced natural resources and biodiversity loss.

Precision livestock farming (PLF) technologies apply the principles of control engineering to automate and provide early warning in livestock farming, allowing farmers to monitor large populations of animals for health and welfare, detect issues with individual animals in a timely manner, and even anticipate issues before they occur based on previous data (Benjamin and Yik, 2019). Recent examples of PLF technologies include monitoring cattle and sheep behavior (jaw movement, grazing and feeding behavior, animal movement) (Laca and DeVries, 2000; Herinaina et al., 2016), detecting vocalizations (screams in pigs), monitoring coughs in multiple species to identify respiratory illness, breath analyses (Burciaga-Robles et al., 2009; Knobloch et al., 2009), and identifying different metabolites (perspiration – sodium and lactate levels, tears – glucose level) (Leopold et al., 2014), saliva – uric acid (Yamaguchi et al., 2013), body temperature (inflammation or pregnancy) and progesterone – pregnancy (Neethirajan et al., 2017).

PLF can enable farmers monitor infectious diseases in farm animals, providing electronic information transfer, e.g. from biosensors, in optimizing animal health, production and management processes on farm, thus improving food safety and availability, as well as maximizing efficient resource use (Norton et al., 2019).

The application of PLF implies measuring variables on the animals (health, welfare, behavioral changes, good productive performance, good reproductive performance) (Tullo et al., 2019), modeling these data to select information (algorithm), and then using these models in real time for monitoring and control purposes. The philosophy of PLF is to assist farmers in monitoring the health and welfare status of their animals in a fully automated and continuous manner (Nastasijević et al., 2017). By doing so, the farmers are able to make quick, pro-active and evidence-based decisions to adjust to changes in animal requirements. The nanobiosensors utilized to detect changes in animal physiology are integrated with the Internet-of-Things (IoT) technology (cloud servers, smart phone applications) for the rapid and real-time reporting of livestock condition on a farm. Therefore, PLF supports the intelligent management of animal health including rapid alert systems to meet the growing global demand for animal proteins, while guaranteeing animal health and welfare, the future sustainability of animal farming, as well as improved food safety (Berckmans, 2017).

3.2. Digitalization on farm

Digital farming (e.g. smart farming & agriculture 4.0) has potential to transform food animal farming systems to become more sustainable by reducing the use of antimicrobials (thus preventing the emergence of antimicrobial resistance, AMR), promoting animal health and welfare, and creating conditions for achieving sufficient supplies of good quality and safe food. Having in mind that global agri-food systems are already facing challenges regarding the increasing demand for animal protein, the process of digitalization of livestock farming can have a beneficial impact by optimizing and increasing overall productivity in a sustainable manner without further pollution of soil, water and other agro-ecological systems, as well as improving resilience and adaptation of the food system to climate change (Cole et al., 2018; Shang et al., 2021).

Digital farming technologies include a broad spectrum of devices and applications, such as sensing systems (e.g. biosensors for the wireless transfer of information based on biochemical interaction between the biomarker and the bioreceptor – Figure 2), Artificial Intelligence/AI (developed algorithms for data processing), cloud computing, IoT, blockchain, as well as smart phone applications for real-time access to obtained information and decision support (Torkey and Hassanein, 2020; Nastasijevic et al., 2020b).

It is of utmost importance to recognize and understand the mechanisms of adoption and dissemination of digital farming technologies by farmers and system level (collection and organization of entities relevant for the adoption and dissemination). The adoption behavior is multi-dimensional and depends not only on farmers but also on the technical, structural, political and economic conditions of the agri-food chain; the adoption of digital farming can also evolve over time, based on the

behavior of farmers and their interactions with the legislative, commercial and political environment (Alexander et al., 2013; Shang et al., 2021). The most important factors influencing the adoption of digital farming technologies are defined in 6 groups (Shang et al., 2021): (I) farm characteristics (farm size, biophysical conditions, livestock ownership, land use, labor availability, farm succession); (II) operator characteristics (education, age, farming as a main occupation, income, computer use, farming experience, innovativeness, knowledge & capacity, risk preference); (III) interactions (consultants, extensions, farmers' associations, technology providers, trade shows,

workshops, information sources); (IV) institutions (subsidy/credit, legislation); (V) attributes of technology (relative advantage – perceived usefulness, complexity – ease of use, compatibility, data safety, trialability, observability); (VI) psychological factors (attitude, subjective norm, perceived behavioral control). The most significant factors influencing the adoption of digital farming include: farm size and biophysical condition, level of education and age of farmers, quality of interaction with consultants and extension services, availability of subsidies and credits, usefulness and ease of use of the technology, and farmers' attitude (Shang et al., 2021).

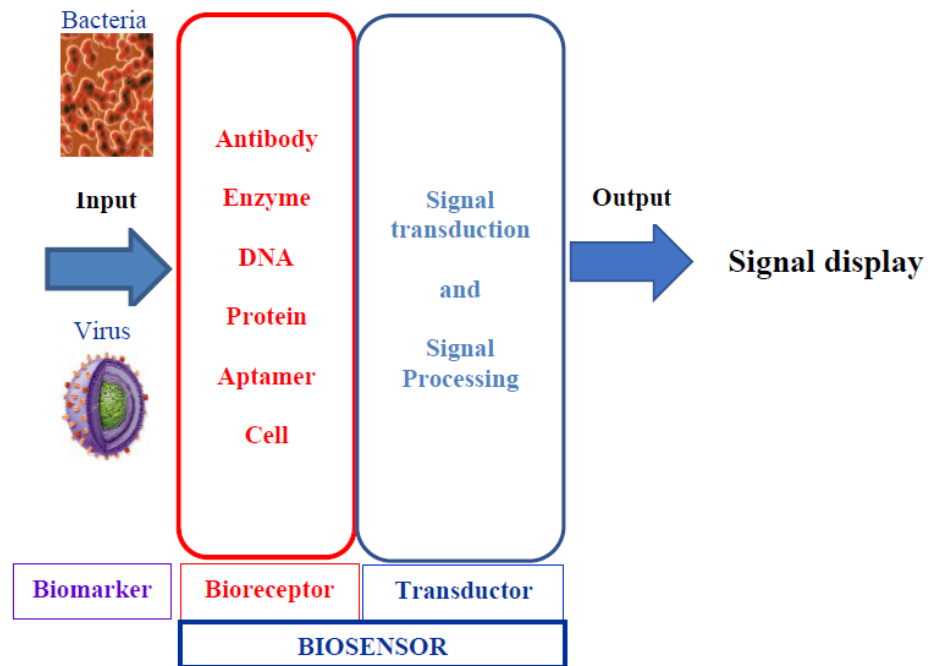


Figure 2. Biosensor principle based on the biochemical reaction between the biomarker and the bioreceptor (adapted from Vidic et al., 2017)

The examples of digital farming are associated with the interface biosensors – cloud computing – IoT – smart phone applications providing valuable and real-time information on animal health and welfare, including some reproductive and nutritional issues. For example, the following animal health and physiological conditions, including animal welfare status, can be effectively monitored by sensing systems: lameness in solipeds (acceleration data by ear tags); locomotion in cows (automatic 3D vision); grazing behavior in cattle and sheep (acoustic sensor for identifying jaw movement, chewing and biting) (Laca and DeVries, 2000); physiological and behavioral stress in animals; vocalization sounds of broilers in response to environmental conditions; cattle and pig cough as an indicator of respiratory disease (Neethirajan et al., 2017); drinking behavior of animals; health status via body temperature (video-based infrared thermography camera); hormone profile for estrus detection (Neethirajan et al., 2017); detection of animal diseases (e.g. brucellosis, bovine tuberculosis, bovine respiratory disease/BRD, bovine viral diarrhoea/BVD, avian influenza virus/AIV, foot and mouth diseases/FMD, mastitis) (Fend et al., 2005; Wang et al., 2009; Knobloch et al., 2009; Montrose et al., 2015; Yang et al., 2015; Tarasov et al., 2016; Martins et al., 2019); and fecal shedding of food borne pathogens (e.g.

Salmonella, *Campylobacter*, *Cl. perfringens*), which is important from the perspective of meat safety (Nastasijević et al., 2019). Further, sensing systems can also represent an added value in providing supplemental information for other methods related to animal welfare assessment based on nutritional status and Body Condition Scoring (BCS) (Lalovic et al., 2020).

Namely, the concentration of major zoonotic food (meat) borne pathogens can be accurately detected by innovative sensing systems (biosensors) based on specific biomarkers for pathogens affecting animal health, such as DNA receptors, glycan, aptamers and antibodies (Halachmi, 2015). A biosensor recognizes a target biomarker characteristic of a pathogen *via* an immobilized sensing element – a bioreceptor (monoclonal antibody, RNA, DNA, glycan, lectin, enzyme, tissue, whole cell). The specific biochemical interaction between the biomarker and the bioreceptor is then converted into a measurable signal by the transducer (Figure 2). Paper-based platforms (microarrays) can be effectively used as affordable, rapid and user-friendly sensing systems under real farm conditions (Vidić et al., 2017).

3.3. Digitalization in abattoirs

To date, there has been limited evidence on the wide commercial and routine adoption of digitalization in abattoirs. However, there are some promising steps towards the transition to digital technologies. Currently, the most frequently used approach is the computer vision system (CVS) monitoring of pathological lesions on carcasses and internal organs, as well as fecal contamination on carcasses (Blagojević et al., 2021). Namely, computer vision, digital image processing and digital image analysis are terms used to describe the process of digital image acquisition (Fernandes et al., 2020). Since regular and routine performance of official veterinary meat inspection protocols at remote small- and medium-scale abattoirs and game handling establishments are usually associated with a relatively high cost of official control per inspected animal, there is potential for cost reduction via live-streamed video generated by CVS (Almqvist et al., 2021).

The potential and benefit of using CVS in abattoirs have been increased in the European Union (EU) since 2014, when a legislative shift was made to allow for a purely visual post-mortem inspection of carcasses of pigs reared under 'controlled conditions', essentially meaning indoors, in order to omit the palpation- and incision-based inspection that was previously necessary (Hill et al., 2013; EC, 2014). In other cases, when *"the epidemiological or other data from the holding of provenance of the animals, the food chain information or the findings of ante-mortem inspection and/or post-mortem visual detection of relevant abnormalities indicate possible risks to public health, animal health or animal welfare, the carcasses and offal of pigs are to undergo additional post-mortem procedures using incision and palpation"* (Commission Regulation (EC) 218/2014).

The application of biosensors (linked with cloud computing and IoT) in abattoirs for the purposes of meat safety monitoring has been very much limited. On the other hand, progress in developing sensing systems has been recorded in recent years, resulting in the creation of biosensors for the detection of food (meat) borne pathogens, such as lateral flow, aptamer-based biosensors for the in-situ quantitative detection of *S. Enteritidis* and *E. coli* O157:H7 at a sensitivity level of 10 colony forming units (CFU)/mL, respectively (Fang et al., 2014; Wu et al., 2015) or DNA-based sensors for the detection of *Campylobacter* in meat (poultry) samples at a detection level of 1.5×10^1 CFU/g (Manzano et al., 2015) or cell-based sensors which have mammalian cells as sensing elements to detect pathogens or toxins of *Clostridium perfringens* (Yoo et al., 2016). The regular and routine use of such biosensors is still not feasible as their performance and detection limits were mainly tested with enriched bacterial suspensions (*in vitro*) with the scarcity of data when using a matrix from a real production environment (e.g. straw, feces, blood).

3.4. Digitalization in meat distribution and retail

The introduction and adoption of digital technologies throughout the meat distribution and

retail sector have already been recognized. The initial use of digitalization is related to the continuous time/temperature (t/T) monitoring of fresh meat (chilled or frozen) via data loggers and/or Radio-Frequency Identification (RFID) tags (Jakubowski, 2015) connected via wireless mode with appropriate software (IoT/blockchain approach) and/or smart phone applications; recently, this has evolved to the level of machine learning methods used to predict temperature and even to detect breaks in the cold chain (Loisel et al., 2021); and/or "smart-packaging" (sensors measuring T or Volatile Organic Compounds/VOCs associated with meat spoilage) during distribution, storage and presentation in retail display cabinets (Mohebi and Marquez, 2015).

The UN World Health Organization has advocated cooperation between competent authorities, manufacturers and consumers to help ensure food safety in global food trade taking into consideration the cross-border nature and complexity of modern food supply chains (WHO, 2020). In addition, the global COVID-19 pandemic has increased consumer awareness of food supply chain transparency. Public concern has arisen regarding food safety and more consumers are expected to carefully select the brands they purchase. Digital traceability solutions such as "smart labeling" and "digital tracing", which provide contact-free and secure product information in a real-time environment, can play a role in reassuring consumers that products are safe to eat (Euromonitor, 2020).

In light of such recommendation, the dynamic process of digitalization of the food (meat) supply chain is of utmost importance in providing good quality, safety and traceability information to consumers, based on which they can make informed choices when purchasing meat/meat products.

Digitalization in the meat supply chain should be based on the integrated farm-to-retail approach to cover all modules along the meat chain, e.g. pre-harvest (farm), harvest (abattoir), and post-harvest (meat processing, distribution, retail), and enable full traceability at the point of retail.

Consumers should also take their part of responsibility related to meat handling and preparation, which belongs to the level of food safety culture. Interestingly, blockchain technology has been overshadowed by investments in Artificial Intelligence (AI) and IoT. Namely, huge price drops in digital sensors such as RFID tags and artificial intelligence software have made food businesses more interested in investing in AI and IoT over blockchain.

Although COVID-19 has put a spotlight on the application of blockchain in food safety and sustainability-based traceability, high costs and lack of clear use cases remain major obstacles to its adoption (Euromonitor, 2020). For example, the use of blockchain technology in the farm-to-retail continuum must be smooth to avoid disruption of existing farming practices and to enable easy adoption. In addition, farmers should not be faced with large financial burdens and governments should potentially offer subsidies or affordable credits. On the other hand, digital technology will provide greater transparency across the food chain to farmers, giving them access to valuable information (Figure 3).

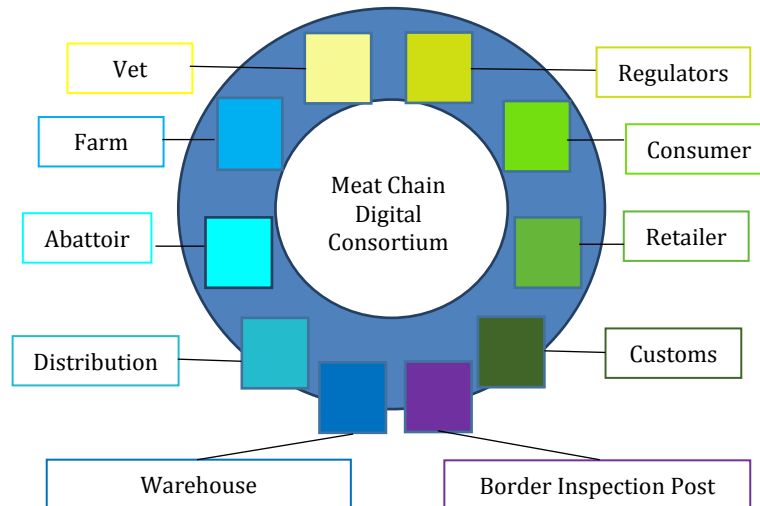


Figure 3. Example of the digitalization model in the meat supply chain (blockchain, AI/IoT)

3.5. New business model and retail modernization

In the era of the fourth industrial revolution, where the use of digital technologies is becoming *conditio sine qua non* in day-to-day life, including the food production and supply chain, the technology that automatically monitors product risk factors (animal health and welfare farm conditions, time, temperature, tamper-resistant packaging, potential for cross-contamination, traceability) will be encouraged. The key stakeholders involved in the food (meat) chain should be motivated to adopt the new business model, e.g. farmers, meat business operators (abattoirs, meat processing), manufacturers of food ingredients, food delivery companies, restaurants, retailers.

Retailers should be encouraged to conduct an independent review of traditional retail food safety programs (aiming for the prevention of food borne diseases and communication with suppliers and consumers), as well as to advance controls of their food safety management in terms of hygienic and technical conditions (facility and equipment design) and use of 'smart kitchen' equipment (for automated time and temperature monitoring).

Special emphasis should be placed on consumers and their participation in the food chain related to evidence-based food choices and educational materials (training manuals and leaflets) on the handling of food purchased or delivered to their home (in particular when it comes to e-commerce and home food delivery) to create a food safety culture at home.

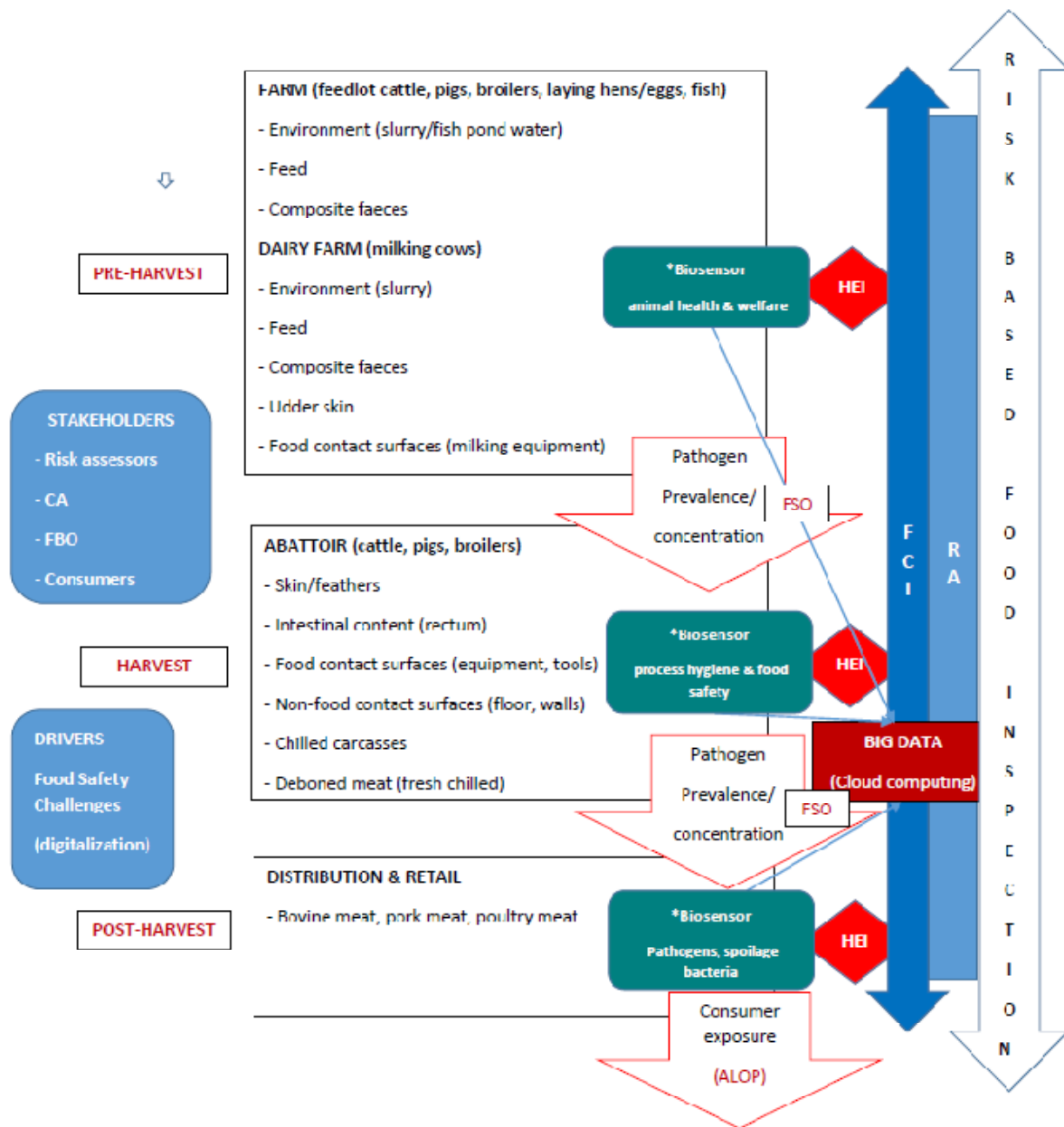
The successful development and adoption of the new business model for the transformation of the food chain are based on the effective and efficient use of digital technologies and their interface with stakeholders throughout the food chain, in particular consumers (e.g. smart-phone applications providing real-time information on a food product from the label barcode).

3.6. Digitalization in the Farm-to-Retail Food Safety Management System (FSMS)

In light of forecasted rapid population growth, the global demand for meat and meat products is about to be increased by 40% in the following 15 years. A major challenge within the next 10 years is how to enable continuous monitoring of animal health within big groups of animals (Berckmans, 2017). Due to the increasing number of animals and the decreasing number of farmers, every farm will house more animals. In the future, a single farm (or animal city) may host 25,000 milking cows, 200,000 fattening pigs, or a few million broilers. Infections in such big groups can have disastrous economic and public health consequences (Berckmans, 2017). For example, in the EU during 2019, 27 Member States reported 5,175 food-borne outbreaks involving 49,463 cases of illness, 3,859 hospitalizations and 60 deaths. In addition, 117 outbreaks, 3,760 cases of illness and 158 hospitalizations were communicated by six non-MS. It has to be highlighted that *L. monocytogenes*-associated outbreaks in the EU were remarkable since this agent was responsible for 349 cases of illness and more than 50% of total outbreak associated deaths (31 deaths; 10 deaths more than in 2018; 29 more than in 2017). Most of the deaths were due to the consumption of meat and meat products (EFSA/ECDC, 2019). Parallel to this, the overuse and misuse of antibiotics in farm animals can lead to increased occurrence of antimicrobial resistance (AMR) associated with food (meat) consumption; AMR outbreaks significantly increased from 10.4% in 2014 to 14.9% in 2017 (ECDC, 2018). The continuous and efficient monitoring of the use of antibiotics in food animals and public and/or regulatory pressure for antibiotic reduction can decrease AMR development and consequently reduce consumer exposure. Digital technologies can play an important role in securing effective and real-time monitoring of animal health, welfare, infection diseases and AMR. The information collected in the continuous digital monitoring system should be incorporated into Food Chain Information (FCI) in both directions, farm-

to-retail (bottom-up) and retail-to-farm (top-down). Such information (sensing systems, blockchain, AI, IoT) should provide a platform for decision-making by risk managers (veterinary inspection, and/or authorized

personnel by FBO) in the meat safety assurance system (MSAS) and should also be based on Harmonized Epidemiological Indicators (HEIs) to enable the effective implementation of the FSMS (Figure 4).



*Indicators detected by biosensor: Pathogen (e.g. *Salmonella*, *Campylobacter*), Animal health (Acute Phase Proteins), Animal welfare (hormones)

ALOP – Appropriate Level of Consumer Protection

CA – Competent Authorities

FBO – Food Business Operators

FCI – Food Chain Information

FSO – Food Safety Objective

HEI – Harmonized Epidemiological Indicators

RA – Risk Analysis (risk assessment, risk management, risk communication)

Figure 4. Food Safety Management System (FSMS) model for the digitalized meat chain

It is worth noting that an epidemiological indicator is defined as “the prevalence or the concentration of the hazard at a certain stage of the food chain or an indirect measure of the hazard that correlates with the human health risk caused by the hazard” (EFSA, 2013). Digitalization along the meat chain can enable the

integration of FCI and HEIs for the improvement and modernization of meat inspection methods and the food safety risk analysis in the farm-to-retail continuum. It is foreseen that HEIs will be used in the bovine/pig/poultry carcass meat safety assurance system (farm-to-chilled carcass system) to help

categorize farms/herds and abattoirs according to the risk related to the hazards, and set hazard-based

targets in/on bovine/pig carcasses and, when appropriate, in bovine/pig farms and herds (Table 1).

Table 1.

Example of Harmonized Epidemiological Indicators for *Salmonella* in the pig carcass safety assurance system (EFSA, 2011)

Indicator (animal/food category)	Meat chain phase	Analytical/ diagnostic method	Sample
HEI 1: <i>Salmonella</i> in breeding pigs	Farm	Microbiology (detection and serotyping)	Pooled (composite) feces sample
HEI 2: <i>Salmonella</i> in fattening pigs prior to slaughter	Farm	Microbiology (detection and serotyping)	Pooled (composite) feces sample
HEI 3: Controlled housing conditions on farm	Farm	Auditing	N/A
HEI 4: Transport and lairage conditions	Transport and lairage	Auditing of time, mixing of batches and reuse of pens in lairage	N/A
HEI 5: <i>Salmonella</i> in fattening pigs – evisceration stage	Abattoir	Microbiology (detection and serotyping)	Ileal content
HEI 6: <i>Salmonella</i> in fattening pigs – carcasses after slaughter before chilling	Abattoir	Microbiology (detection and serotyping)	Carcass swabs
HEI 7: <i>Salmonella</i> in fattening pigs – carcasses after slaughter and after chilling	Abattoir	Microbiology (detection and serotyping)	Carcass swabs

*Not applicable

Risk managers should decide on the most appropriate indicator(s) to be used, either alone or in combinations, at national, regional, abattoir or farm/herd level, depending on the purpose and the epidemiological situation. It is recommended that risk managers should define harmonized requirements for the controlled housing conditions of farms. Evidently, there is a need for the additional improvement FCI/HEIs and their integration into the FSMS in the farm-to-retail continuum, including the development of HEIs up to the retail level, to ensure the inclusion of risk assessment data from the post-harvest meat chain module (distribution, retail and food safety culture). This should be effectively achieved by the dynamic digitalization of the meat supply system to provide benefits for all major stakeholders in the meat chain (farmers, meat business operators, competent authorities, consumers).

4. Conclusions

The digitalization in the meat chain is coming with the fourth industrial revolution (4S). Recent developments in Artificial Intelligence, Internet of Things and blockchain technologies will have a tremendous and disruptive effect on the meat chain supply system in terms of improving the monitoring and surveillance of hazards at multiple points along the meat chain (pre-harvest, harvest, post-harvest), in the farm-to-retail continuum, as well as providing better quality of information to consumers for informed decisions regarding food purchase. The farm-to-fork food chain continuum should be managed to provide an appropriate level of consumer protection (ALOP). This can be achieved by science-based risk assessment, which includes information about the prevalence and

concentration of major public health hazards (epidemiological indicators) of zoonotic origin (*Salmonella*, *Campylobacter*, *Listeria monocytogenes*, *Yersinia*, Shiga toxin-producing *Escherichia coli*/STEC) in all modules along the food (meat) chain: farm – transport – slaughterhouse – meat processing – distribution – retail – consumers.

The integration of digital technologies to the Food (Meat) Safety Management System or Meat Safety Assurance System will enhance the integration of Food Chain Information and Harmonized Epidemiological Indicators along the meat chain, from farm to retail (bottom-up) and vice versa from retail to farm (top-down). Further, meat chain digitalization will increase the transparency and visibility of all actors involved in meat production, processing, distribution and retail (farmers, meat business operators, competent authorities, retailers), and provide the basis for benchmarking producers and retail chains, as well as pro-active consumer participation in defining future food policies at the national and global level. However, the current FSMS approach is based on the farm-to-chilled carcass continuum and there are no defined harmonized epidemiological criteria at the retail level. Therefore, there is a need for future and deeper research, which should include the development of HEIs at the distribution/retail level and their integration into the digitalized meat safety assurance system.

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Declaration of competing interest

Authors declare that no personal and/or financial relationship with other people or organizations is present in this review.

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