

# Meat safety: Risk based assurance systems and novel technologies

Ivan Nastasijević<sup>1\*</sup>, Slavica Vesković<sup>1</sup>, Milan Milijašević<sup>1</sup>

**Abstract:** The meat industry has undergone substantial changes over the previous several decades due to development of new technologies in primary production (food animals on farm) — precision livestock farming, sensing systems; slaughter & dressing — automation and robotization; and meat processing — precision fermentation, 3-dimensional printed meat. The current, traditional meat inspection (ante-mortem and post-mortem), based on visual inspection, palpation and incision, had not been changed since the end of the nineteenth century. Although this traditional approach was effective at the time it was introduced for detection of classical zoonoses (brucellosis, tuberculosis, cysticercosis, anthrax infection), it was not fully efficient in terms of the current needs for consumer protection. Namely, public health hazards associated with meat are, nowadays, connected to zoonotic food (meat) borne pathogens (Salmonella, Campylobacter, Shiga toxin-producing *E. coli*, *Listeria monocytogenes*), faecally excreted by healthy animals, which are responsible for the majority of human illnesses attributed to meat consumption; traditional meat inspection cannot respond effectively to detect these food borne hazards, but can even increase cross-contamination due to palpation and/or incision procedures. Therefore, there is a need to develop a novel, modern meat inspection system which will be risk-and evidence-based — the meat safety assurance system or carcass safety assurance system. Such a modern system should be based on risk management and meat inspection protocols supported by analysis of Food Chain Information/Harmonised Epidemiological Indicators in the farm-to-chilled carcass continuum.

**Keywords:** meat safety, assurance system, meat inspection, cultured meat.

## Introduction

**Meat and high nutritional value.** The consumption of meat is highly esteemed in most places in the world considering it as a food product with high nutritional value rich in highly bioavailable proteins, vitamins (B complex), essential amino acids and microelements (zinc, iron) (Williams, 2007; McAfee et al., 2010; Bohrer, 2017). There is a relatively small percentage of people (2–10%) who choose not to consume meat, mainly in developed nations (Corrin & Papadopoulos, 2017). However, this percentage is still significant on a global level having in mind food markets and vegetarian and/or vegan diets. It is important to have the evidence-based data on nutritional content and bioavailability of diets based on meat versus vegetarian/vegan-based diets so that food choices from the public health level can be better evaluated. A number of scientific papers and reviews addressed the nutritional content of meat, e.g. red meat, poultry and seafood (Pereira & Vicente, 2013; Williams, 2007; Wood et al., 2008; Sikorski, 2012) and non-meat products rich in proteins, e.g. crops, legumes (Multari et al., 2016).

Most non-meat foods contain only 20–60% of the protein density of meat, and consideration needs to be made when replacing meat in the diet with non-meat foods. Additionally, when protein cost was evaluated, meat and non-meat foods had a similar cost when expressed as grams of protein/\$US (Bohrer, 2017). The total amount of zinc and iron was similar in meat and some non-meat foods. Lastly, meat-based diet is also associated with a higher digestibility and availability of nutrients. 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.** Global meat production is projected to be 16% higher in 2025 than in the period up to 2015 (OECD/FAO, 2016). The major reason for this total increase of meat production is attributed to developing countries due to 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 the growth in total meat production in response to expanding

<sup>1</sup>Institute of Meat Hygiene and Technology, Kacanskog 13, 11000 Belgrade, Republic of Serbia.

\*Corresponding author: Ivan Nastasijević, [ivan.nastasijevic@inmes.rs](mailto:ivan.nastasijevic@inmes.rs)

global demand for this more affordable animal protein compared to red meats (OECD/FAO, 2016). The main reasons that contribute to making poultry a 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.). In the bovine meat sector, cow herd liquidation occurred in major producing regions which led to a decrease of beef production in 2015 (OECD/FAO, 2016). Beef production stabilised and increased from 2016 and onwards with higher carcass weight, thus neutralising the decline in cattle slaughter. Pig meat production increased from 2016, mainly driven by China, where herd size stabilised 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 the consolidation of the pork sector, a decrease in pig meat production on a global scale has been 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 disease; estimations are that around 30% of the Chinese pig population (150–200 million pigs) has been infected by ASF by mid-2019 (Mason-D`Croz et al., 2020). The sheep meat sector recorded growth of 2.1% per annum in the previous decade due to increased production in China, Pakistan, Sudan and Australia (OECD/FAO, 2016).

*Global meat trade.* World meat output comprising bovine, pig, poultry and ovine meat was estimated at 330 million tonnes in 2017, which was a 1% increase from the previous year (FAO, 2018). Considering the main meat producing countries, total meat output increased in Argentina (+4.8%), Russian Federation (+4%), Mexico (+3.5%), United States (+2.8%), India (+2.7%), Brazil (+2.1%); stagnation was recorded in the EU and China; meat output declined in South Africa (−2.5%). Poultry meat output was the most widely produced meat, reaching 120.5 million tonnes in 2017 (up 1.1% from 2016), which is around 36% of the total meat output on a global scale. This was followed by pig meat (118.7 million tonnes, +0.7%), which was around 35.9% of the global meat output; bovine meat (70.8 million tonnes, +1.5%), which comprised around 21.5% of the global meat production; and ovine meat (14.9 million tonnes, +1.3%), representing 4.5% of the total meat output volume on a global scale (FAO, 2018). World meat exports reached 32.7 million tonnes in 2017 (2.7% higher than in 2016). The

highest increases in export were recorded in Turkey (+36.3%), Argentina (+22%), Thailand (+8.8%) and the United States (+5.6%). Declines in meat exports occurred in Chile (−9.5%), South Africa (−8.3%) and the EU (−3.4%). On the other hand meat imports increased in Angola (+25.3%), the Russian Federation (10.4%), Japan (+9.4%) and Viet Nam (+7.7%), while imports declined in Saudi Arabia (−11%), China (−6.3%), the EU (−4.2%) and Canada (−1.8%). In general, in 2017 the total meat trade output increased for bovine, poultry and ovine meat, while pig meat trade declined. With such development, poultry meat has become the most widely produced and internationally traded meat type worldwide (FAO, 2018).

*Global meat safety issues.* Meat safety is always at the forefront of public health and social-economic concerns (Sofos, 2008). Major meat safety challenges are associated with hazards that can be considered as a traditional, new or emerging, which can involve increased virulence and/or low infectious dose and with resistance to antibiotics or resistance to other food related stresses (Sofos, 2008). These hazards enter the meat chain in multiple points along the farm — abattoir — meat processing — distribution — retail — consumer continuum. Traditional microbiological/parasitic hazards are *Trichinella* spp., *Brucella* spp., *Mycobacterium bovis*, *Bacillus anthracis* 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. 'big six': O26, O45, O103, O111, O121, O145 (USDA FSIS, 2011) or O26, O103, O145, O111, O145 (EFSA, 2020), *Salmonella*, e.g. '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 safety of raw meat and poultry, while *Listeria monocytogenes* remains a concern in ready-to-eat (RTE) processed meat products (Sofos, 2008). Chemical hazards are related to environmental contaminants which enter meat chain (mycotoxins, heavy metals, PCBs), veterinary drugs (antibiotics, sulphonamides), hormones and food additives (nitrites, polyphosphates). Other challenges include the need for development of rapid testing and pathogen detection methodologies with sufficient sensitivity and specificity, traceability systems (blockchain technology), agreement and allocation of responsibilities between veterinary and public health authorities regarding monitoring and surveillance systems for zoonotic diseases (including food

borne), establishment of government policy regarding maximum allowed contamination level-appropriate level of protection (MACL-ALOP) for food which should reach the consumer (Nastasijevic *et al.*, 2020), as well as establishment of risk-based food safety objectives in meat production/processing, together with complete and routine implementation of risk-based food safety management system, hazard analysis and critical control points (HACCP).

*Integrated approach in the meat chain (farm-to-abattoir continuum/farm-to-chilled carcass).* Significant changes, backed up with the technological development in modern food animal farming and meat production systems has led to a significant change in the public health threats that originate from meat in developed countries. Classical zoonoses, such as tuberculosis, trichinellosis, cysticercosis or anthrax infection became much less important (Uzal *et al.*, 2002; Buncic *et al.*, 2019), while bacterial agents carried and excreted (primarily via faeces) by food animals without symptoms or originated from environment, such as *Campylobacter*, *Salmonella*, STEC, *Listeria monocytogenes* and *Yersinia enterocolitica* have become the most relevant (Figure 1).

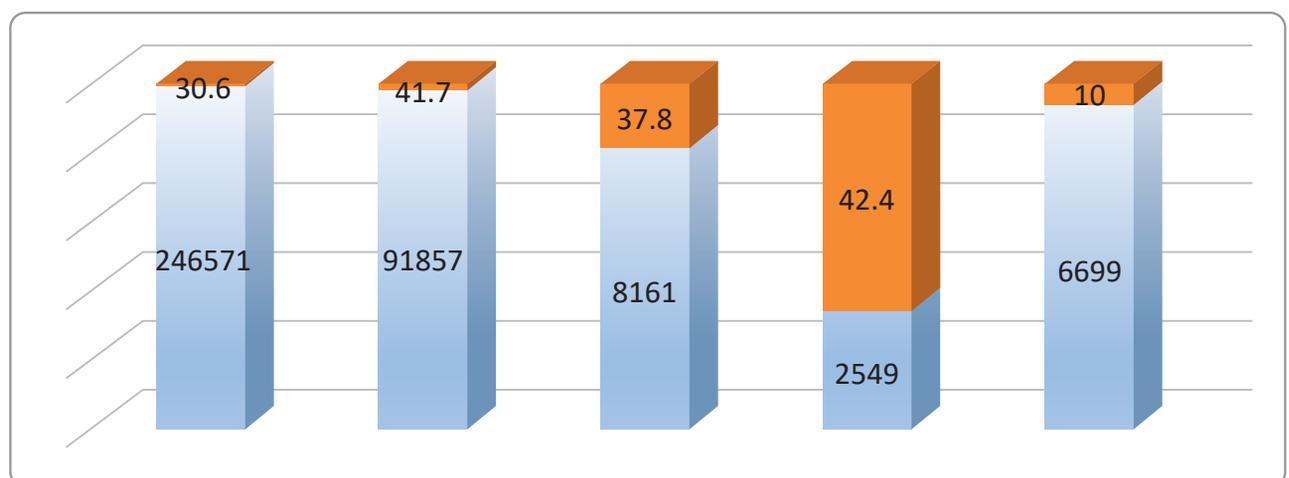
## Materials and Methods

A literature review was performed by analysing published scientific papers and the major sources of information from scholarly databases such as Web of Science, EBSCO, PubMed Science Direct and Wiley. The scientific opinions and official web sites of inter-governmental organisations and agencies were also searched (EFSA, ECDC, FAO, WHO,

OIE). This review identified relevant articles (research and review papers, technical reports by international organisations and databases), published in domains of meat inspection, zoonotic foodborne pathogens and meat safety assurance system, including the related public health impact. The selection criteria chosen to identify the relevant articles within the scope of this review and the objectives of this paper were as follows: 1) focus on the meat inspection protocols, traditional and novel approaches with well-established databases regarding meat safety assurance system; 2) focus on the potential for improvement of the current meat inspection and meat safety assurance system and the need for future research, and 3) novel and futuristic technologies in meat production. Search string included the following key words: meat, inspection, meat safety assurance system, zoonotic, food borne pathogens, public health, precision livestock farming, harmonised epidemiological indicators, food chain information, biosensors, automation, robotization, cultured meat, precision fermentation, 3D printing. However, some geographical restrictions were taken, by including selected countries with intensive experience and well-established, integrated meat safety assurance systems.

## Biological meat-borne hazards

The main food (meat) borne hazards (mainly of bacterial origin) in the EU Member States (MS) in 2018 were, in decreasing order based on incidence, as follows: *Campylobacter*, *Salmonella*, STEC infections, *Yersinia*, *Listeria monocytogenes*, *Trichinella* spp. and *Toxoplasma gondii*.



**Figure 1.** The relevance of the five major food-borne pathogens in the meat chain in the EU, in 2018 (adapted from EFSA/ECDC, 2019)

### Zoonotic food (meat) borne bacteria

**Campylobacter.** In the EU in 2018, there were 246,571 confirmed cases (64.1/100,000) of campylobacteriosis in MS, with 30.6% hospitalisation rate and 60 reported deaths (EFSA/ECDC, 2019). In the meat safety context, the most relevant are poultry meat and *Campylobacter jejuni* and *coli*. Overall, 37.5% of fresh broiler meat samples were positive in 2018 in the EU. *Campylobacter* was found in 34.6% of tested slaughter batches (neck skin from chilled broiler carcasses), 26% of tested broiler flocks and 71.6% of tested turkeys on farm. Strict implementation of biosecurity measures in primary production and GMP/HACCP during slaughter may reduce colonisation of broilers with *Campylobacter*, and contamination of carcasses (EFSA/ECDC, 2019; Nastasijević et al., 2020). In the abattoir, additional risk reduction can be achieved by using hot water/chemical decontamination or freezing of carcasses. At the consumer level, marination of poultry meat and adequate thermal processing can reduce the risk substantially (Nastasijević et al., 2020). Campylobacteriosis is also associated with seasonality, with sharp increases during summer and early autumn. Recently, a new microbiological criterion was introduced in the EU to reduce the number of food borne outbreaks and improve public health; the criterion is for process hygiene at broiler slaughter, defining the maximum number of *Campylobacter* as 1,000 cfu/g in/on neck skin of chilled broiler carcasses (EU, 2017a). It is estimated that *Campylobacter* could be reduced by > 50% if no batches exceed this critical limit.

**Salmonella.** In the EU in 2018, 91,857 confirmed cases of food borne salmonellosis were reported in MS. Salmonellosis thus remained the second most commonly reported gastrointestinal infection with an incidence of 20.1/100,000, 41.7% hospitalisation rate and 119 reported deaths. Most *Salmonella* outbreaks were associated with *S. Enteritidis* and most outbreaks were linked with poultry meat intended to be cooked before consumption (EFSA/ECDC, 2019). *S. Infantis* was the most predominant serovar isolated in broilers (36.5%) and broiler meat (56.7%). On farm level, the most predominant food animals associated with *Salmonella* presence (in decreasing order) were fowl, pigs, turkeys, bovine and ducks and geese.

Monitoring of *Salmonella* is conducted during preharvest (feed, farm animals), harvest (abattoirs, cutting plants) and postharvest (retail, catering) (EU, 2003). Regulatory limits for food are set up in Regulation (EC) 2073/2005, defining process hygiene

criteria (PHC) and food safety criteria (FSC); compliance with these criteria must be verified by the food business operator based on their self-monitoring plan. The reporting of food borne salmonellosis disease outbreaks in humans is mandatory according to the Zoonoses Directive (EU, 2003a). In the meat safety context, the most relevant are poultry meat (*S. Enteritidis*, *S. Typhimurium* and *S. Infantis*) and pork meat (*S. Typhimurium*).

Strict implementation of biosecurity measures in primary production and GMP/HACCP during slaughter can prevent/reduce colonisation of broilers with *Salmonella* and contamination of carcasses. In the abattoir, additional risk reduction can be achieved by using hot water/chemical decontamination. At the consumer level, marination of poultry meat and adequate thermal processing can reduce the risk substantially (Murphy et al., 2002). Salmonellosis is also associated with seasonality, with a sharp increase during summer months.

The EU MS are obliged to set up *Salmonella* National Control Programmes (NCP) in poultry with the aim to reduce the prevalence of serovars of major importance for public health, e.g. *S. Enteritidis*, *S. Typhimurium*, *S. Infantis*, *S. Virchow*, and *S. Hadar* (EU, 2003).

**STEC infections.** In the EU in 2018, 8,161 confirmed cases of Shiga toxin-producing *E. Coli* (STEC) infections in humans were reported in MS. The incidence rate was 2.28/100,000, with 37.8% hospitalisation rate (411 Haemolytic Uremic Syndrome — HUS cases) and 11 reported deaths. A total of 48 food borne outbreaks were recorded and the major food sources were cheese, milk, bovine meat, vegetables and juices. In the meat safety context, bovine meat is considered as a major source of STEC-food borne infections (4% of bovine meat was STEC-positive in retail, 5.6% in the processing plant and 2.4% in the abattoir), followed by ovine meat (10.9% being STEC positive) and pork meat (4.8% STEC positive). Most STEC infections were associated with serogroup O157 due to this being the predominant testing method, while many others were linked with non-O157 serogroups. STEC serotypes associated with food borne outbreaks usually possessed distinctive virulence factors, e.g. *Stx+* (shiga toxin) and *eae+* (intimin, adherence factor for intestinal mucosa). In the EU, six major STEC serogroups of public health importance are recognised (O157, O26, O111, O103, O145, O104:H4). However, the only regulatory requirement is the food safety criterion for sprouts (sprouted seeds) at the retail level (EU, 2005; EU, 2013). In the US, the Food Safety and

Inspection Services of the U.S. Department of Agriculture (USDA FSIS, 2012) declared six non-O157 Shiga toxin-producing *Escherichia coli* (STEC) O groups (O26, O45, O103, O111, O121, and O145) to be adulterants in meat. These top six STEC O groups were associated with 75% to 80% of human infections (USDA FSIS, 2012). STEC infections also showed a seasonal trend and were associated with a sharp increase during summer months.

*Listeria monocytogenes*. In the EU, 2549 cases of food borne listeriosis were reported in 2018, with notification rate of 0.47/100,000 population. The highest number of reported cases was reported in Germany, Spain and France (684, 372 and 338, respectively), due to improved surveillance, while the lowest number was reported in Cyprus, Malta and Croatia (1, 1 and 4, respectively). During a four year period, a seasonal pattern was observed with high summer peaks and lower winter occurrence. The hospitalisation rate of all reported cases was 42.4%, with 229 reported deaths. This implies that although the notification rate and number of reported cases of listeriosis is lower than campylobacteriosis and salmonellosis, high hospitalisation and mortality rate mean *L. monocytogenes* is a pathogen which should be carefully monitored in the food chain, in particular in chains involving the age group over 64 years which is the vulnerable group of consumers and other vulnerable groups, e.g. pregnant women, immunocompromised persons and individuals with chronic diseases. Although the food vehicles causing listeriosis with strong evidence (in decreasing order) were category 'vegetables and juices' 'mixed food' 'fish and fish products', 'vegetables and juices' and 'crustaceans, shellfish, molluscs', an important portion of food borne listeriosis is also attributed to the consumption of ready-to-eat (RTE) meat products (Lakicevic & Nastasijevic, 2017; EFSA/ECDC, 2019). This is mainly related to fermented meat products with probable sources of infection being the raw material (meat used for manufacturing of fermented meat products). Therefore, understanding the presence and colonisation of this pathogen, and source tracking it in the meat production environment is of utmost importance for control and prevention of meat-borne listeriosis. An effective and potent food safety management tool for tracking of *L. monocytogenes* is whole genome sequencing (WGS), enabling the specific detection of *L. monocytogenes* strains in production environment and their tracking throughout the production lines (Nastasijevic et al., 2017). In addition, synergistic application of Good Agriculture Practice and Good

Farming Practice at the farm level, along with Good Manufacturing Practice (GMP), Good Hygiene Practice (GHP) and HACCP in abattoir and retail/catering are important for effectively controlling this pathogen (Lakicevic and Nastasijevic, 2017).

*Yersinia*. Yersiniosis was the fourth most commonly reported zoonosis in the EU MS during 2018, with 6,699 confirmed cases. The incidence rate was 1.6/100,000 with 27 hospitalisations and 1 reported death (EFSA, 2018; ECDC, 2019). *Yersinia enterocolitica* was the most relevant species for human infection. The main sources of *Yersinia* were bovine meat, pork meat and RTE meat products — 30.0%, 5.0% and 5.9%, respectively. On farm, the proportion of pigs with *Yersinia* was 0.4% and that of other domestic livestock (bovine, sheep, goats, farmed rabbits, farmed reindeers, etc.) was 1.7%. In the meat safety context, pork meat and meat products had the highest importance, having in mind that 26.7% of the total of 15 outbreaks in 2018 were linked to consumption of pig meat (EFSA, 2018; ECDC, 2019).

#### Zoonotic meat borne parasites

*Trichinella* spp. In 2018, 66 confirmed cases were reported in the EU (EFSA/ECDC, 2019). The incidence rate was 0.1/100,000, and that was the lowest rate ever recorded since the introduction of surveillance. The highest notification rate was recorded in Bulgaria followed by Romania. In 2018, 114 reported cases of food borne trichinellosis were reported with pig meat as the predominant source. A low prevalence of *Trichinella* was also confirmed in the EU in hunted wild boar (0.13%), in the period from 2014–2018 (EFSA/ECDC, 2019). The EU legislation requires testing of all *Trichinella*-susceptible animals intended for human consumption (EU, 2015), i.e. domestic pigs (fattening and breeding animals), farmed wild boar and solipeds.

*Toxoplasma gondii*. No food borne toxoplasmosis was recorded in the EU during 2018 (EFSA/ECDC, 2019). In addition, no single food borne outbreak has ever been reported to EFSA since the start of data collection in 2004. However, 194 confirmed cases of congenital toxoplasmosis were reported, with 78.9% of all registered cases in France. The highest prevalence of *Toxoplasma* infections in food animals were reported in cattle (27.8%) and in small ruminants (sheep and goats; 18.3%). Different diagnostic methods contributed to the bias in interpreting results from testing. Mainly blood samples and sometimes tissues and organs are tested with direct

methods — PCR or immunohistochemistry or indirect methods — ELISA, immunofluorescence assay, or complement fixation test, to detect antibodies (EFSA/ECDC, 2019). Results from different MS are not comparable due to differences in sampling strategy, sampling schemes and testing methods. Age of animals and production systems at farm level can influence the occurrence of *Toxoplasma* (EFSA/ECDC, 2019).

### Zoonotic meat borne viruses

Among the foodborne viruses most important for public health, comprising Norovirus (NoV), Hepatitis A virus (HAV) and Hepatitis E virus (HEV), only HEV has also been identified as a zoonosis (Koopmans, 2012; EFSA, 2017; O'Shea et al., 2019). It is associated primarily with pigs. In the EU, over the last 10 years more than 21,000 acute clinical cases with 28 fatalities have been notified with an overall 10-fold increase in reported HEV cases; the majority (80%) of cases were reported from France, Germany and the UK. However, as infection in humans is not notifiable in all MS, surveillance and number of reported cases differs between countries (EFSA, 2017).

The diagnosis of HEV infections in humans is not routinely conducted in most laboratories, and therefore, it is considerably under-diagnosed (De Keukeleire & Reynders, 2015). However, since HEV-associated cases have become more frequent in recent years, novel and improved diagnostic tools and screening strategies have been developed (Abravanel et al., 2017). Main control options focus on prevention of HEV contamination. Also, high risk groups (underlying liver disease, immunocompromised, pregnant) should be advised against eating raw/undercooked meat and liver derived from wild boars and domestic pigs (Buncic, 2015). HEV is also considered as an occupational disease, with abattoir workers being the most frequently exposed.

### Prions

Bovine spongiform encephalopathy (BSE) is a disease in cattle. It belongs to a group of fatal neurodegenerative diseases affecting humans and animals called transmissible spongiform encephalopathies (TSEs) (Fernández-Borges et al., 2017; Leemans, 2019). They are caused by the abnormal form of a cell protein called prion protein (PrP). Since the discovery of BSE in cattle, only two cases have been confirmed in species other than cattle: one goat in France and one goat in the UK (EFSA, 2018). To

date, among TSEs in animals (BSE, Classical scrapie, atypical scrapie, chronic wasting disease (CWD) and transmissible mink encephalopathy (TME)), only the classical BSE agent has been evidenced to cause TSE in humans (EFSA, 2018). BSE has three different presentations: classical BSE, H-type atypical BSE and L-type atypical BSE (Ubagai et al., 2020). Classical BSE is the only form that can be transmitted to humans through the consumption of contaminated meat, causing variant Creutzfeldt-Jakob disease (vCJD), which was first diagnosed in 1996. Although there is no epidemiological evidence that classical scrapie is zoonotic, the zoonotic potential of atypical scrapie agent needs further investigation (Goldmann, 2018). Nevertheless, transmission studies of human PrP in transgenic mice or primates suggest that some TSE agents other than the classical BSE agent in cattle (namely L-type atypical BSE, classical BSE in sheep, TME, CWD agents) might have zoonotic potential; and studies even indicate that the potential of the L-type atypical BSE agent appears similar or even higher than that of the classical BSE agent (Buncic, 2015). With regards to present risk mitigation measures, the current policy of removing specified risk material (SRM) in slaughtered ruminants from the food chain enables around one logarithm reduction of the relative infectivity associated with the carcass of an infected animal. This policy, along with controls of ruminant feeds in respect to SRM, remains the main BSE/TSE control strategy (Buncic, 2015).

### Chemical hazards in the meat chain

Chemicals can occur in the meat chain due either to their existence in the environment through unintentional contamination of food, or to their intentional use somewhere along the meat production chain (Nova & González-Schnake, 2014). Industrial pollutants are unintentional contaminants of foods, but can be difficult to control, in spite the existing regulations. On the other hand, agricultural chemicals are deliberately applied to land or crops during production, so their use can be both regulated and controlled (Meurillon et al., 2018). Some toxic chemical compounds can occur naturally in foods and in the environment (e.g. mycotoxins).

The rate of ingestion of chemical hazards by food animals can be either higher or lower than the rate of their excretion. In the former case, accumulation of chemicals occurs. In the latter case, animals have a 'decontaminating' effect from the public health perspective. Hazards that accumulate can be a greater public health risk than those which do

not accumulate, because if animals are exposed even only to low levels of accumulating hazards but over extended time, their tissues can finally contain levels that pose a risk to consumers (EU, 2017b). With chemical hazards that accumulate, older animals are a higher risk than younger animals due to prolonged time allowed for accumulation of contaminants in target tissues. In the EU, MS and third countries that export food of animal origin (meat and meat products) are obliged to implement national monitoring programme for residues in the food chain (EU, 2017b). The main chemical hazards are presented in Table 1.

### Risk ranking and Harmonised Epidemiological Criteria

EFSA adopted scientific advice for the modernisation of meat inspection across the EU. Modern food producing animals and meat production systems went through significant changes over several

previous decades due to technological and scientific development. The public health importance and attention gradually shifted from classical zoonoses (tuberculosis, brucellosis, trichinellosis, cysticercosis and anthrax) to zoonotic food borne pathogens (mainly) of bacterial origin, e.g. *Salmonella*, *Campylobacter*, STEC, *Listeria monocytogenes* (Edwards et al., 1997; Uzal et al., 2002; Buncic et al., 2019). These, zoonotic meat borne hazards of bacterial origin cannot be detected by old-fashioned meat inspection (palpation, incision) and their presence on carcasses, due to cross-contamination during slaughter and dressing, can be only monitored through the control of process hygiene (self-control plan, as an integral component of Hazard Analysis Critical Control Point-HACCP system) based on carcass swabbing (mainly wet-dry, non-destructive method). Animals intended for slaughter can intermittently faecally shed zoonotic bacteria on farm, during transport, livestock markets and in the abattoir lairage. Cross-contamination can occur in all the

**Table 1.** Main groups of chemical hazards in the meat chain

Industrial pollutants	Agrochemicals	Growth promoters	Veterinary medicines	Natural substances	Food additives	Packaging compounds
<i>Heavy metals</i> Lead, Arsenic, Mercury, Cadmium, Copper, Fluorine, Selenium	<i>Insecticides</i> <i>Chlorinated hydrocarbons</i> Dihlor-difenil-trihloretan (DDT), Endrin, Aldrin/Dieldrin, $\beta$ -Hexachlorocyclohexane (BHC) <i>Organophosphates</i> -- Coumaphos, Malathion, Diazinon  <i>Herbicides</i>	<i>Hormones and hormone-like substances</i>  Synthetic hormones (DES), Natural hormones (Oestradiol, Progesterone, Testosterone), Fungal oestrogens (Zearalenone)	<i>Antibiotics</i>  Penicillins, Aminoglycosides, Tetracyclines, Cephalosporins, Macrolides, Quinolones, Nitro compounds (Nitroimidazoles, Nitrofurans)	<i>Mycotoxins</i>  Aflatoxins, Ochratoxins	<i>Curing agents</i>  Nitrites, Polyphosphates, Sodium chloride	<i>Plastics</i>  VC-monomers, Plasticisers
<i>Halogenated hydrocarbons</i>  Polychlorinated biphenyls (PCBs), Polychlorinated naphthalenes (PCNs), Dioxins		<i><math>\beta</math>-agonists</i>  (Trenbolone),	<i>Sulphonamides</i> (Sulphametazines)	<i>Algal toxins</i>  Paralytic Shellfish Poison (PSP), ASP (Amnesic Shellfish Poison), DSP (Diarrhetic Shellfish Poison), AZP (Azaspiracid Shellfish Poison)	<i>Antioxidants</i>  Butylated hydroxyanisole (BHA), Butylated hydroxytoluene (BHT), Gallates	<i>Pigments/Inks</i>
		Thyreostatics			<i>Preservatives</i>  Sulphite, Benzoate, Sorbic acid	
					Smoke	

**Table 2.** Ranking of main biological and chemical hazards identified for each animal species (EFSA, 2011; 2012; 2013a; 2013b)

Species	Biological hazards				Chemical hazards
	High	Medium	Low	Undetermined	
Cattle	STEC <i>Salmonella enterica</i>	N/A**	<i>Campylobacter spp.</i> ( <i>thermophilic</i> ) <i>Yersinia enterocolitica</i> / <i>pseudotuberculosis</i> <i>ESBL/AmpC E. coli</i> <i>Cysticercus</i> ( <i>Taenia saginata</i> ) <i>Mycobacterium bovis</i>	<i>Toxoplasma gondii</i> <i>Trichinella spp.</i>	Dioxins, dioxin-like polychlorinated biphenyls (DL-PCBs)
Sheep and goats	STEC <i>Toxoplasma gondii</i>	N/A	<i>Campylobacter spp.</i> ( <i>thermophilic</i> ) <i>Salmonella enterica</i> <i>Yersinia enterocolitica</i> / <i>pseudotuberculosis</i> <i>ESBL/AmpC E. coli</i>	<i>Trichinella spp.</i>	Dioxins, Dioxin-like polychlorinated biphenyls (DL-PCBs)
Porcines	<i>Salmonella enterica</i>	<i>Yersinia enterocolitica</i> / <i>pseudotuberculosis</i> <i>Toxoplasma gondii</i> <i>Trichinella spp.</i>	<i>Campylobacter spp.</i> ( <i>thermophilic</i> ) STEC <i>ESBL/AmpC E. coli</i> Cysticercus ( <i>Taenia solium</i> ) <i>Mycobacterium avium</i> ( <i>hominissuis</i> )	N/A	Dioxins, Dioxin-like polychlorinated biphenyls (DL-PCBs)
Solipeds	<i>Trichinella</i>	N/A	<i>Campylobacter spp.</i> ( <i>thermophilic</i> ) <i>Salmonella enterica</i> <i>Yersinia enterocolitica</i> / <i>pseudotuberculosis</i> STEC <i>ESBL/AmpC E. coli</i>	<i>Toxoplasma gondii</i>	Phenylbutazone*, Chemical elements ( <i>cadmium</i> )
Poultry (broilers)	<i>Campylobacter spp.</i> ( <i>thermophilic</i> ) <i>Salmonella enterica</i>	<i>ESBL/AmpC E. coli</i>	N/A	<i>E. coli</i> ( <i>process hygiene</i> )	Dioxins, Dioxin-like polychlorinated biphenyls (DL-PCBs), chloramphenicol, nitrofurans, nitroimidazoles
Farmed game (deer)	<i>Toxoplasma gondii</i>	N/A	N/A	N/A	N/A
Farmed game (wild boar)	<i>Salmonella enterica</i> <i>Toxoplasma gondii</i>	N/A	N/A	N/A	N/A
Farmed game (reindeer, ostriches, rabbits)			N/A		N/A

**Legend:** \*EFSA recommended that phenylbutazone, which is not allowed in the food chain, be specifically included in the National Residue Control Plans (NRCs) for solipeds. \*\*N/A — not applicable

aforementioned phases along the meat chain related to animal-animal and animal-environment contact.

Based on this, EFSA issued a scientific opinion to provide identification and ranking of the major meat borne hazards according to their risk for public health (EFSA, 2013a, Table 2).

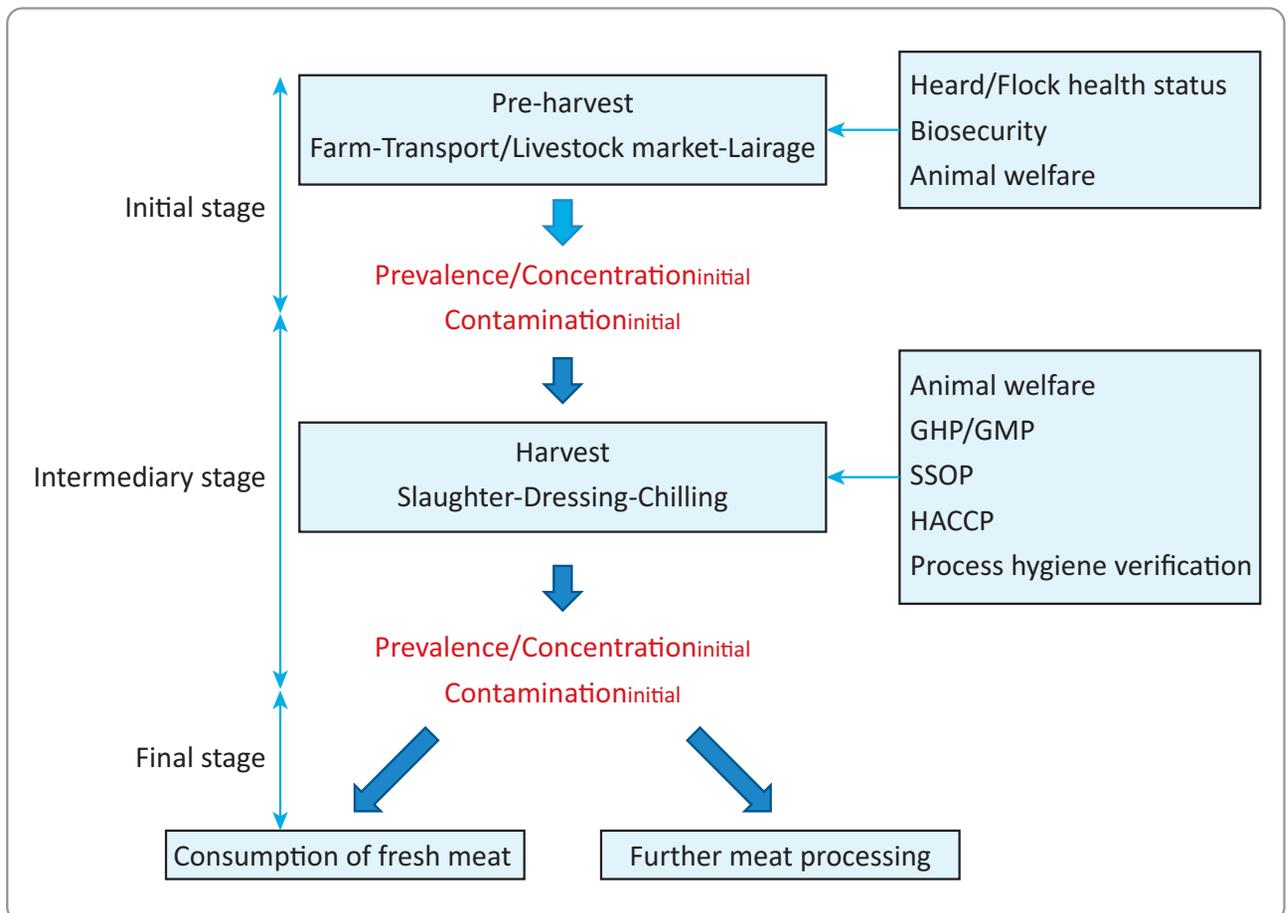
**Biological hazards.** The priority ranking was based on assessment of their impact according to incidence of disease, the severity of the disease in humans and source attribution (evidence that consumption of meat from the various species is an important risk factor for the disease).

**Chemical hazards.** Risk ranking of chemical hazards was based on the five-year outcomes of the National Residue Control Plans for 2005–2010 and other voluntary testing programs as well as substance-specific criteria, such as the chemical's toxicological profile.

EFSA also proposed harmonised epidemiological indicators (HEI). The indicators will be useful in the context of the proposed integrated meat safety assurance system, enabling the categorisation of farms, flocks or herds and abattoirs according to

potential risk and the setting of microbiological targets for carcasses.

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, 2013b, Figure 2). The indicators can be used to consider improvement and modernisation of meat inspection methods and to carry out risk analysis to support such decisions. It is foreseen that the indicators will be used in the bovine/pig/poultry carcass meat safety assurance system to help categorise farms/herds and abattoirs according to the risk related to the hazards, as well as setting appropriate specific hazard-based targets in/on bovine/pig carcasses and, when appropriate, in bovine/pig farms and herds. Risk managers should decide on the most appropriate indicator(s) to use, 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 the harmonised requirements for the controlled housing



**Figure 2.** A model to set up harmonised epidemiological indicators for a meat safety assurance system based on the prevalence and/or level of the hazard in the farm-chilled carcass continuum

conditions of farms. In the EU, MS should plan to organise training regarding the implementation of the indicators and the reporting of data generated by the implementation of Directive 2003/99/EC (EU, 2003).

### Risk based meat safety assurance system

In 2005, Codex Alimentarius Commission issued a Code of Hygienic Practice for Meat (CAC, 2005) and recommended integrated and risk-based approach to achieving meat safety. In this document, it is suggested that “hygiene measures should be applied at those points in the meat chain where they will be of greatest value in reducing food borne risks to consumers”; a greater emphasis on prevention and control of contamination during all aspects of producing and processing meat should be applied. Levels of hazard control in meat chain should correspond with required levels of consumer protection. In continuation with such approach, EFSA recently proposed a framework for a novel, flexible and dynamic risk-based meat safety assurance system (EFSA, 2011; 2012; 2013a; 2013b). The introduction and implementation of such a system is expected to be a slow and careful process, and it would evolve over time after collecting initial experience, fine tuning and verifying in practice. The modern risk-based meat inspection should be based on food chain information (FCI) from farm to abattoir (bottom-up) and vice versa (top-down), as well as HEI related to major meat borne pathogens and chemical contaminants. Risk managers will have the possibility to operate within the meat safety assurance system, taking into consideration FCI and HEI and making decisions based on the situation related to the level/type of meat inspection that should be applied, e.g. classical ante-mortem and post-mortem inspection (including palpation and incision) or visual-only inspection based on ante-mortem and post-mortem observation of the animal intended for slaughter. Visual-only inspection will be enabled when animals are sourced from farms with high levels of biosecurity and where animal health status and animal welfare are maintained at high levels (e.g. pathogen-free farms). Successful implementation of risk-based meat inspection should be carried out within the meat safety assurance system comprising several systems/elements/criteria in the farm-to-abattoir continuum (e.g. precision livestock farming, FCI, HEI, food safety management in abattoir, meat inspection — classical and/or modern, risk-based).

### Precision livestock farming (PLF)

PLF applies principles of control engineering using electronic information transfer, e.g. from biosensors to optimise animal health, production and management processes on farm. PLF is a multidisciplinary science that requires close and effective collaboration among animal scientists, physiologists, veterinarians, ethologists, engineers, and information and communication technology (ICT) experts (Berckmans, 2017).

Since the global farm animal population will increase by 70% by 2050, a major problem in the next decades will be to ensure continuous monitoring of animal health within big groups of animals (Berckmans, 2017). Farms will hold more animals due to increasing numbers of animals and decreasing numbers of farmers. It is predicted that in the future a single farm (animal city) could have 25,000 milking cows, 200,000 fattening pigs or a few million broilers. Infections in such large conglomerations of food animals could have disastrous consequences, in particular when reduced antibiotic use is a priority due to prevent antimicrobial resistance (AMR). The alternative strategy could be development of vaccines, but this is time-consuming and their efficacy in big herds must be closely monitored to evaluate effectiveness (Berckmans, 2017). Therefore, potential for infections in these animal cities will be high and also related to the spread of zoonotic food borne agents to consumers via food, including meat. PLF supports intelligent management of animal health including rapid alert systems to meet growing human demand for animal proteins, while guaranteeing animal health and welfare, the future sustainability of animal farming, and improved food safety (Berckmans, 2017).

The main purpose of PLF is to obtain real-time, valid information regarding both (i) animal health (e.g. production diseases) and associated economic gains or losses, and (ii) food (meat) safety (e.g. zoonotic food borne pathogens — *Salmonella*, STEC, *Campylobacter*, *Yersinia*) and associated consumer health issues affecting public health. Therefore, PLF is currently considered as a state-of-the-art engineering endeavour towards sustainability in (primary) food production improving, consequently, consumers' health through more effective public health protection (Nastasijević et al., 2017). Another big issue is the environmental impact of the livestock sector. It is estimated that more than 90% of the NH<sub>3</sub>, 37% of CH<sub>4</sub> and 65% of N<sub>2</sub>O in the atmosphere comes from the livestock sector (FAO, 2013).

PLF offers a real-time monitoring and managing system for farmers, as follows: (i) a real-time warning is issued when something goes wrong so immediate action can be taken by the farmer to solve the problem, (ii) problems during animal rearing are detected, allowing immediate management action. Therefore, PLF is a powerful tool for measuring animal variables (good health, welfare, behavioural changes, good productive performance, good reproductive performance), modelling the acquired data to select information, and using these models in real time for monitoring and control purposes (Berckmans, 2017).

The main objectives of PLF are to manage individual animals by continuous real-time monitoring (24/7) regarding animal health, welfare, production, reproduction, environmental impact and food safety outcomes. PLF monitoring tools are:

- (i) camera/real-time image analyses
- (ii) microphone and real-time sound analyses
- (iii) sensors around or on the animal (temperature detection)
- (iv) biosensors (microfluidic) used for rapid tests (stress hormones, acute phase proteins, pathogen presence).

The point of these systems is to detect less-than-ideal conditions and provide an initial response regarding animals' behavioural changes. The first signs of problems picked up by the PLF sensing technology can be based on image analysis, sound analysis and sensors on the body (Berckmans, 2017).

A living organism is much more complex than any mechanical, electronic, or ICT system and is considered as a complex, individually different, time-varying, dynamic (CITD) system. Each living organism is individually different in responses to environmental stimuli or stressors (Berckmans & Aerts, 2016; Quanten *et al.*, 2006).

A good example of practical implementation of PLF image-based sensing systems is the early warning system for broiler houses, eYeNamic, to monitor general problems in broiler houses (> 30,000 animals), where it is very hard to observe such a high number of birds (Figure 3). The system is based on three or four cameras mounted on the ceiling of the house so that distribution of the birds can be monitored and the broilers' behaviour analysed in real time.

Another example of a sound-based PLF sensing system is monitoring animal health status on cattle farms via detection of calf cough episodes (Berckmans, 2017; Carpentier *et al.*, 2018).

PLF can be also used to monitor behaviour of animals (ovines, cattle) in pasture during grazing by using the animal-borne accelerator, which has 24/7 monitoring capability. This PLF sensing system can detect animal movements during grazing, standing, walking and lying (Barwick *et al.*, 2020). Examples of PLF applications on pig farms include not only traditional environmental indicators (temperature, humidity, CO<sub>2</sub>), but also direct measures of animal responses such as feed intake sensors, growth monitors,

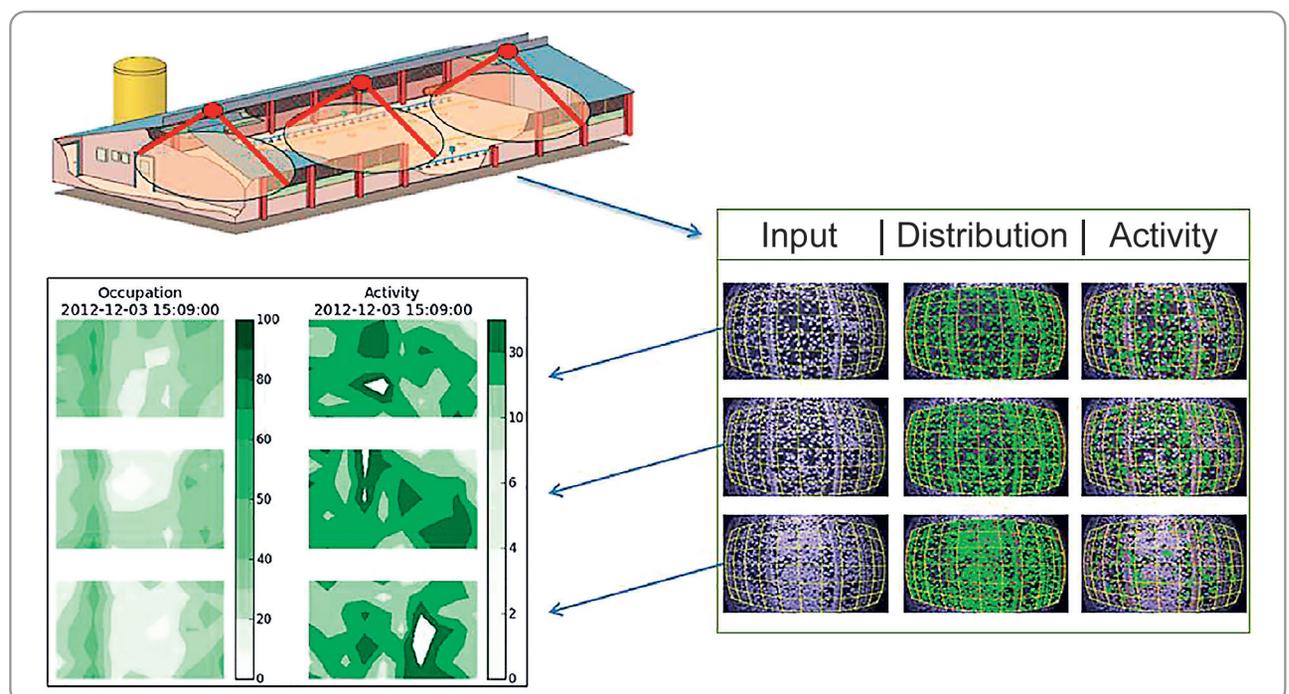


Figure 3. eYeNamic system — poultry farm (three top-view cameras) (adapted from Berckmans, 2017)

behaviour (cameras) and sound (microphones). The PLF concept is still rather new in the EU pig industry, and the number of farmers and companies engaged in pig farming businesses that are using PLF technology is increasing. A commercially available PLF sensing technology is associated with pig cough monitors, automatic weighing devices and camera systems. Furthermore, the business intelligence software is still under development and requires continuous improvements. The EU Commission recently supported a big project related to application of PLF in commercial farms in Europe, i.e. EU-PLF project (2012–2016). A database was created based on 20 fattening periods. Early warning tools for farmers were developed. In addition, automated welfare assessment based on electronic sensor output has been developed (Vranken & Berckmans, 2017).

The application of PLF allows optimal use of knowledge and information in the monitoring and control of processes on farm. In addition, such an approach allows extension to the further step in the meat chain, helping to define the most effective control measures and risk mitigation strategies at the abattoir level. Therefore, PLF can be used strategically to support FCI flow in the farm-to-chilled carcass continuum and to facilitate decision-making by the risk managers, e.g. official veterinarian and/or authorised auxiliary appointed by the food business operator in terms of the scope and type of the ante-mortem and post-mortem inspection. Overall, PLF can serve effectively in supporting a risk-based meat safety assurance system (Nastasijević et al., 2017).

### Food Chain Information

Modern meat inspection should incorporate a more risk-based approach for protecting public health against food (meat) borne biological hazards than has been the case to date. Meat inspection should fulfil four major objectives: human health, animal health, animal welfare (ante-mortem inspection) and meat safety (post-mortem inspection) (Felin et al., 2016; EU, 2019). Therefore, a comprehensive and integrated pork/beef/poultry carcass safety assurance system in the farm-abattoir continuum should be developed to ensure the effective control of major meatborne public health hazards, “with the primary production stage playing an essential role in managing these risks” (EFSA, 2011).

FCI should include data on the prevalence/concentration of major food borne hazards of public health importance at farm, transport and lairage, and abattoir (HEI). These data should be result from

targeted sampling (pooled faeces on farm or carcass swabs at abattoir), microbiological detection (and serotyping) and auditing (animal welfare and biosecurity on farm; and GHP/HACCP at abattoir).

For example, in the EU, there is the intention to shift to visual-only post-mortem inspection of pigs. The official veterinarian (OV) (risk manager) decides on additional post-mortem inspection procedures, such as incisions and palpations, based on declarations in the food chain information (FCI) and ante-mortem inspection. However, it is of essential importance that the OV should be able to assess prior to slaughter which pigs are to be subjected for visual-only meat inspection and which need additional inspection procedures (Felin et al., 2016). The decision can be based on one or any combination of the FCI, ante-mortem inspection (including verification of animal welfare), post-mortem inspection or any other data regarding the animal that might, in the OV’s opinion, indicate a possible risk to public health, animal health or animal welfare.

Meaningful FCI and collection & communication of inspection results (FCI/CCIR) interpreted and advised by the veterinarians can be a vehicle for positive change as a part of the modernisation of meat inspection (FVE, 2015). The most effective approach to control the main hazards in the context of meat inspection is an integrated meat safety assurance system for all animals, combining a range of available preventive and control measures applied in the farm-abattoir continuum.

### Harmonised Epidemiological Indicators

For the most relevant foodborne biological hazards, EFSA has also proposed HEIs. The indicators will be useful in the context of the proposed comprehensive meat safety assurance system and risk based meat inspection, enabling the categorisation of farms, flocks or herds and abattoirs according to potential risk and the setting of microbiological targets for carcasses. The improvements to existing practices or alternative methods for meat inspection have been recommended, while the implications of the proposed changes to current practices for surveillance of animal health and welfare have been studied.

*Bovine HEI.* These indicators were defined to serve in developing a bovine carcass safety assurance system. By definition, 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 (such as audits)

that correlates with the human health risk caused by the hazard” (EFSA, 2013b).

Indicators should help categorise farms/herds and abattoirs according to the risk related to the meat borne hazards of public health importance in the bovine meat chain, and be the basis of appropriate specific hazard-based targets in/on bovine carcasses and in bovine farms/herds. These hazards are as follows: *Salmonella*, human pathogenic STEC, cysticercus (*Taenia saginata*) and *Mycobacterium bovis*; the last two are already covered by the current, traditional meat inspection process (EFSA, 2013b). The indicators can be applied at national, regional, abattoir and/or farm/herd level, depending on the purpose and the epidemiological situation of the country. Furthermore, the indicators can be used alone or in combination. For *Salmonella* and STEC, the proposed HEI include microbiology-based indicators, which will give specific information on *Salmonella* and STEC infection or contamination in the animal (on farm), hide or carcass (in abattoir). HEI based on audits at farm or transport conditions and

visual inspection of bovine hide are also proposed, which will give a more general assessment of microbiological risk and, when used in combination with microbiological HEI, will support assessment and knowledge of the *Salmonella*/STEC risk. Lastly, the proposed indicators for *Salmonella*, STEC, cysticercus (*Taenia saginata*) and *Mycobacterium bovis* can also be applied to classify countries, regions, farms, abattoirs, slaughter batches and animals according to the infection status or risks related to the hazard. This approach will enable the comparability of data between the EU MS, as well as internationally (EFSA, 2013b).

For example, eight HEI were recommended for pathogenic STEC in bovine meat, within a bovine carcass safety assurance system in the farm-abattoir continuum (Table 3).

*Pig HEI.* The proposed HEI for pig meat, in the farm-abattoir continuum, encompasses the major meat borne hazards of public health importance, as follows: *Salmonella*, *Yersinia enterocolitica*, *Toxoplasma gondii*, *Trichinella*, Cysticercus (*Taenia*

**Table 3.** Harmonised epidemiological indicators for human pathogenic STEC in the bovine carcass safety assurance system (adapted from EFSA, 2013b)

Indicator (animal/food category)	Meat chain phase	Analytical/diagnostic method	Sample
HEI 1: Practices which increase the risk of introducing pathogenic STEC into the farm (purchase policy, mixing with other herds, access to pasture, access to surface water)	Farm	Auditing	N/A*
HEI 2: On-farm practices and conditions	Farm	Auditing	N/A
HEI 3: Pathogenic STEC status of the group(s) of bovine animals containing animals to be slaughtered within one month	Farm	Microbiology	Pooled (composite) faeces or floor samples
HEI 4: Transport and lairage conditions	Transport and lairage	Auditing	N/A
HEI 5: Visual inspection of hide conditions of animals at lairage (clean animal scoring system)	Abattoir	Visual inspection	N/A
HEI 6: Pathogenic STEC on incoming animals (after bleeding and before dehidng)	Abattoir	Microbiology	Hide swabs
HEI 7: Pathogenic VTEC on carcasses pre-chilling	Abattoir	Microbiology	Carcass swabs
HEI 8: Pathogenic VTEC on carcasses post-chilling	Abattoir	Microbiology	Carcass swabs

**Legend:** \*Not applicable

**Table 4.** Harmonised epidemiological indicators for *Salmonella* in the pig carcass safety assurance system (adapted from 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) faeces sample
HEI 2: <i>Salmonella</i> in fattening pigs prior to slaughter	Farm	Microbiology (detection and serotyping)	Pooled (composite) faeces sample
HEI 3: Controlled housing conditions at 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 process before chilling	Abattoir	Microbiology (detection and serotyping)	Carcass swabs
HEI 7: <i>Salmonella</i> in fattening pigs – carcasses after slaughter process and after chilling	Abattoir	Microbiology (detection and serotyping)	Carcass swabs

\*Not applicable

*solium*) and *Mycobacterium Avium*, subsp. *hominis-suis*. For example, seven HEI are proposed for *Salmonella* in the context of pig carcass safety assurance system (Table 4), as follows: HEI 1 (on farm; *Salmonella* in breeding pigs), HEI 2 (on farm; *Salmonella* in fattening pigs prior to slaughter), HEI 3 (on farm; controlled housing conditions), HEI 4 (transport and lairage conditions), HEI 5 (in abattoir; *Salmonella* in fattening pigs at evisceration; ileal content), HEI 6 (in abattoir; *Salmonella* on pig carcasses, after dressing/before chilling), HEI 7 (in abattoir; *Salmonella* on pig carcasses, after chilling).

**Poultry HEI.** The poultry carcass safety assurance system should be based on HEI with regard to the most relevant food borne hazards of public health importance. These hazards are as follows: *Campylobacter*, *Salmonella*, and bacteria carrying extended spectrum  $\beta$ -lactamase (ESBL)/AmpC genes (*ESBL/AmpC E. coli*). Four HEI are proposed for the poultry carcass safety assurance system as follows (Table 5): HEI 1 (on farm; parent flock; *Salmonella* & *ESBL/AmpC E. coli*), HEI 2 (on farm; production flock; *Salmonella*, *Campylobacter* & *ESBL/AmpC E. coli*), HEI 3 (abattoir; incoming batches; *Campylobacter* & *ESBL/AmpC E. coli*) and HEI 4 (abattoir; carcass after chilling; *Salmonella*, *Campylobacter* & *ESBL/AmpC E. coli*).

Sampling of poultry carcasses should be based on the available FCI, including results from feed controls. The frequency of sampling for farms should be adjusted accordingly. The poultry meat inspection should be based on FCI (EFSA, 2012). It means that poultry flocks intended for slaughter should be classified into food safety risk categories, so that slaughter procedures and/or decisions on fitness for consumption can be adapted to the health status and food safety risk presented by the flock/batch (Nastasijević et al. 2020). The main responsibility for such a system should be allocated to the FBO, whereby compliance is to be verified by the competent authority (i.e. veterinary inspection). Defined microbiological targets should be defined in primary production (on farm; prevalence/concentration of hazards at flock level) and in slaughter (in abattoir; prevalence/concentration of hazards on carcass).

Therefore, the HEI for poultry carcass safety assurance system should be monitored and used to categorise poultry production flocks (e.g. broilers) into specific risk categories (higher risk flocks and lower risk flocks). Such categorisation should be an integral component of FCI. Risk manager (i.e. competent authority and/or official auxiliary, designated FBO staff and/or abattoir worker) should make decisions accordingly and direct the incoming

**Table 5.** Harmonised epidemiological indicators for the poultry carcass safety assurance system (adapted from EFSA, 2012)

Indicator (animal/food category)	Meat chain phase	Analytical/diagnostic method	Sample
HEI 1: <i>Salmonella</i> & <i>ESBL/AmpC E. coli</i> in parent flock	Farm	Microbiology (detection and serotyping)	Pooled (composite) faeces sample
HEI 2: <i>Salmonella</i> , <i>Campylobacter</i> & <i>ESBL/AmpC E. coli</i> in production flock	Farm	Microbiology (detection and serotyping)	Pooled (composite) faeces sample
HEI 3: <i>Campylobacter</i> & <i>ESBL/AmpC E. coli</i> in incoming batches intended for slaughter	Abattoir	Microbiology (detection)	Ileal content
HEI 4: <i>Salmonella</i> , <i>Campylobacter</i> & <i>ESBL/AmpC E. coli</i> in carcasses after chilling	Abattoir	Microbiology (detection and serotyping)	Neck skin samples or carcass swabs

batches to the higher risk lines (slaughter lines with high GHP level, high risk reduction capacity, including decontamination of carcasses; intended for higher risk flocks) and lower risk lines (slaughter lines with lower/regular GHP level, lower risk reduction capacity, based on regular HACCP implementation and verification, testing — PHC and auditing). In addition, HEI defined at abattoir level should be used for risk classification of the abattoirs; this categorisation can be used for risk management purposes as described above (e.g. diverting high risk poultry flocks to abattoirs with higher risk lines).

#### *Modern meat inspection in the context of carcass safety assurance system*

Farm holdings and the meat industry have undergone substantial changes over recent decades due to improvements to and development of biosecurity, animal welfare, animal health, and slaughter/dressing and meat-processing technology. Meat as a potential source of food borne disease outbreaks has been studied over this time in numerous scientific projects. It is known that in the EU and other developed regions, within the meat chain, the public health focus has now shifted from classical zoonoses (brucellosis, tuberculosis, trichinellosis, anthrax) to food (meat) borne pathogens (*Salmonella*, *Campylobacter*, STEC O157/non-O157, *Yersinia*, *Listeria monocytogenes*) that are, nowadays, the major source of human food borne illness. These zoonotic food borne pathogens are usually faecally excreted (shed) by clinically healthy animals and can contaminate animal hides, skins or feathers which, in turn, leads to cross-contamination of carcasses (bovine, pig, poultry) during slaughter and dressing

procedures. The current, traditional meat inspection system (observation, palpation, incision) is not fully effective in detecting these zoonotic food borne pathogens of public health importance. The risk-based meat inspection system needs to be developed and implemented to increase the level of control of food borne pathogens important for public health and to help ensure meat safety.

The prevention/control of cross-contamination at abattoir can be achieved with strict implementation of GHP and a risk-based food safety management system, e.g. HACCP (Nastasijevic *et al.*, 2016), which can also encompass interventions (e.g. carcass decontamination). Therefore, it is of utmost importance to ensure the carcass microbiological safety before the meat will be distributed for final consumption (fresh chilled or fresh frozen meat) or further processing (fermented or pasteurised meat products). Since the slaughter and dressing procedures are to be completed with the final chilling at the abattoir (also slowing and preventing the growth of pathogens), the adopted approach means meat safety should be achieved only within the farm-to-chilled carcass continuum or with a carcass safety assurance system.

The modern and risk-based meat inspection system should be, therefore, based on FCI supported with defined HEI at three phases in the meat chain: (i) farm, (ii) transport & lairage, and (iii) abattoir. FCI should encompass data from farm holdings — categorisation of farms (biosecurity, animal welfare, animal health), transport and lairage (animal welfare, slaughter logistics) and abattoir — categorisation of abattoirs (GHP/HACCP, risk-reduction capacity of slaughter line — high risk versus low risk slaughter line). The HEI should provide data on prevalence/

level of major food (meat) borne hazards (*Salmonella*, *Campylobacter*, STEC, ESBL/AmpC *E. coli*) at different phases along the meat chain (farm, transport & lairage, abattoir) and are integral part of FCI. The risk manager (OV, designated staff with FBO, supported by the Official Auxiliary and abattoir staff) should make risk-based decisions about the level of ante-mortem and post-mortem inspection, e.g. whether it will encompass detailed clinical (ante-mortem) examination and detailed post-mortem inspection (including palpation and incision) or the inspection will be visual-only (EFSA, 2011; 2012; 2013b). As suggested, whenever possible, the palpation and incision should be omitted since these practices may increase the cross-contamination of carcasses. So, the visual-only meat inspection provided within the carcass safety assurance system should be based on FCI. This means that when animals/flocks intended for slaughter are sourced from farm holdings with low risk (based on HEI), they can be subjected to visual-only inspection and still provide the defined level of meat safety assurance (Buncic et al., 2019).

## Novelties

Substantial changes have occurred in the global meat industry over the past century due to development of technology. The changes encompass increased automation and robotization, production of alternative meat using precision fermentation technology, and 3-dimensional (3D) printing of meat. These novel approaches to meat harvest/production should decrease the labour-dependant process (which can be of critical importance in emergency situations and crises such as the COVID-19 pandemic), while also providing climate change resilience and environmental sustainability.

### *Automation and robotization*

Automation and robotization have led to significant increases in slaughter line (conveyer) speed for beef, pork, sheep, poultry and fish operations and have begun to take over the meat processing business. The meat industry is changing slaughter methods from conventional manual handling to an automated and robot-driven process. For example, the fastest line currently observed in broiler slaughter line enables speed at 13,500/h (Barbut, 2014). The automated pig slaughter/dressing lines include separation of the pelvic bone, carcass opening, breastbone splitting and neck clipping; these automated

lines are now used in many pig abattoirs and run with capacities varying from 300–1280 pigs per hour (Anonymous, 2018). The automation and robotization in beef slaughter has certain limitations regarding development of technology for the slaughter process; this has been quite limited partly due to the biological variation in animals and the cost/benefit of applying complex technology (Madsen et al., 2006). Most of the development was recorded in the area of manually operated tools which have been improved to ease the physical work for operators or tools developed for improving the hygienic quality of slaughter. For example, in the USA there is a development allowing a high line speed in beef slaughter of 300 head/per hour; it is achieved by dividing slaughter and dressing processes across more meat handlers (operators) and by ensuring the animals slaughtered are relatively homogenous in size (uniformity of carcass conformation), as slaughter lines are usually specialised for steers or heifers. Several pieces of equipment are duplicated and processes are divided across several machines, e.g. hide pulling. These plants run in several shifts (Madsen et al., 2006).

However, cattle are mainly slaughtered at lower line speeds worldwide. In the EU, most of large-scale abattoirs run in single shifts at line speeds from 30–75 head/per hour and these plants are seldom specialised, which means they operate with all types of cattle (Madsen et al., 2006). This implies the new, automated technology must be flexible and should match the large biological variation of carcass dimensions. In addition, beef slaughter is usually carried out at regional level due to animal welfare and zoonotic issues as well as geographical constraints. Since individual abattoirs are too small to undertake a large research and development (R & D) task, it seems necessary to join investments in technology development between interested parties at international level. This will reduce the risk, as there will be lower individual financial contribution and it will also ensure a better match with the EU market requirements. Joint R & D should prioritise projects that can have a reasonable payback time and provide advantages regarding hygiene and food safety (Madsen et al., 2006). The recommended development in beef slaughter is related to: automatic cleaning of dirty hides (including belly) prior to slaughter; automatic bung cutting, neck and breast opening; automatic hide pulling (critical for reducing carcass cross-contamination with food borne pathogens); removal of head and tail; automatic separation (cutting) of hind and forequarter; automatic

splitting and removal of the spinal cord (SRM) in one process. Automated deboning is more complex and cost-benefit analysis should be carried out to justify such automation (Madsen *et al.*, 2006).

On the other hand, modern technologies are now common in red meat (pork) and poultry meat harvest (slaughter/dressing, chilling). Shorter time is allowed for deboning; robots are designed to cut meat and they are replacing traditional manual operations. However, this can also be a challenge regarding meat safety because high speed equipment is not always equipped to respond to frequent variations in carcass size/conformation and, therefore, requires development and installation of tailor-made sensors and IT control systems. Automation and robotization requires progress in breeding and genetics to provide greater carcass uniformity, which would help in operating automated equipment (Barbut, 2014). Some alternative approaches have been also recently suggested, like the meat factory cell (MFC) (Alvseike *et al.*, 2018). The MFC concept is different from the conventional slaughter and dressing approach that uses the conveyer system with workers positions along the slaughter line at numerous operational stations. MFC is based on individual cell stations instead of a conveyer; the slaughter and meat primal cutting is carried out in a way that carcass is disassembled from “outside-in”, where limbs, neck, back and loin are removed before internal organs, so that primal cuts’ cross-contamination is minimised (Alvseike *et al.*, 2018). However, this concept and its advantages related to improvement of hygiene, food safety and cost benefit are under development and consideration.

Novel development related to automation and robotization in the meat industry (i.e. slaughter and dressing) could have a substantial impact on improvement of meat safety due to reduced cross-contamination of carcasses and reduced human labour engagement. On the other hand, for effective outcome, it will require ongoing progress in genetics and breeding strategies to provide greater carcass uniformity, which is essential to allow efficient operation of automated equipment.

### *Precision fermentation*

The advancement in technology based on meat that is comprised of animal cells grown outside an animal in a bioreactor is already ongoing and could come to fruition in the foreseeable future (Reis *et al.*, 2020). Products such as “cell-based meat” are genetically identical to conventional meat products.

Cell-based meat is also referred to by others as “clean meat”, “lab-grown meat”, “cultured meat” or “in-vitro meat”. The production of cell-based meat is related to the technology called precision fermentation (Anonymous, 2019). Precision fermentation, through programming of microorganisms to produce desired complex organic molecules, will allow the production of protein tailored to the personal needs of a consumer — the “food as software” approach (where individual molecules engineered by scientists are uploaded to databases, and molecular cook-books that food engineers anywhere in the world can use to design products in the same way that software developers design applications). This model will also enable constant improvement of the product, so each new version will be superior and cheaper than the last. It also ensures a production system that is completely decentralised and much more stable and resilient than industrial animal agriculture, with fermentation farms located in or close to towns and cities, strongly supporting development of peri-urban agriculture and providing a solid basis for food security worldwide (Tubb & Seba, 2019).

Growing muscle tissue in culture media from animal stem cells to produce meat theoretically eliminates the need to sacrifice animals. Cultured meat could in theory be constructed with a range of different characteristics and be produced faster and more efficiently than traditional meat. The technique to generate cultured muscle tissues from stem cells was described long ago, but only recently have commercially produced cultured meat products started to appear on the market (Stephens *et al.*, 2018). The technology is still at an early stage and prerequisites of implementation include a reasonably high level of consumer acceptance, and the development of commercially-viable means of large scale production. Recent advancements in tissue culture techniques suggest that production could be economically feasible, provided the final product has physical properties in terms of colour, flavour, aroma, texture and palatability that are comparable to conventional meat (Kadim *et al.*, 2015).

Such technological development will have a disruptive impact on traditional meat production (rearing food producing animals intended for slaughter and meat production) and the meat chain as a whole. As perceived, precision fermentation is the deepest, fastest and most consequential disruption in the agri-food sector since the first domestication of plants and animals ten thousand years ago. This means cell-based (meat) proteins will be five times cheaper by 2030 and ten times

cheaper by 2035 than existing animal proteins; they will also be superior in all key quality attributes, e.g. more nutritious, healthier and with better taste (Tubb & Seba, 2019). For example, in the US, the impact on industrial farming will be significant; by 2030, the number of cows will have fallen by 50% and the cattle farming industry will be faced with serious economic perspectives. In general, all businesses in the meat value chain (crop farmers, livestock farmers, meat processors) will be affected with this technological development. The disruptive changes will be economic, environmental, social and geopolitical. Economic changes are the forecasted collapses of farmland values (by 40–80%), of crop farming due to decreased need for animal feed and of meat processing businesses in countries with high GDP input related to animal farming. The environmental impact will be related to the fact that, by 2035, 60% of the land currently used for livestock and feed production will be freed for other uses and greenhouse gas emissions from cattle will drop by 60%, including the 50% decrease of drinking water consumption by cattle. Social changes will be related to the greater food (meat) quality, with more nutritious, better tasting meat, as well as cheaper and more accessible product for consumers; job losses are predicted, in particular, in beef and dairy production and associated industries of 90% by 2035 (Tubb and Seba, 2019). The geopolitical impact is the trading shift due to decentralised food (meat) production and decreased impact of climate change in comparison to traditional livestock farming; most likely, the major meat producers and exporters (US, Brazil, the EU) will lose their geopolitical advantage over countries that are currently dependant on importation of meat. Countries currently importing animal products will more easily produce these products domestically at a lower cost, using modern production methods (Tubb and Seba, 2019).

The rapid development of cell-based meat will have striking and disruptive impact on the current understanding of the livestock and meat chain, as a whole, including the meat safety assurance system. The upcoming development and new reality of this novel technology will not only dramatically change the profile of the meat value chain, but also will change consumer perception because cultured meat is supposed to be pathogen-free since it is produced under precisely controlled conditions. A new paradigm for a meat safety assurance system associated with this novel technology should be developed in the foreseeable future.

### 3D Printing of meat

3D printing is an emerging technology for the food (meat) industry, providing an excellent opportunity to utilise meat by-products for the manufacturing of customised meat products. This technology uses computer-aided design (CAD) software assisting a digital manufacture machine in the generation of three-dimensional objects without any additional tool (Noorani, 2017). The combination of nutritionally balanced ingredients and novel internal structures can be integrated into a multi-material 3D model that meets specific individual needs, such as chewing and swallowing difficulties (Dick et al., 2019). This is important, in particular, for elderly consumers dealing with swallowing and mastication difficulties; the PERFORMANCE project was dedicated to solving these issues and improving 3D printing according to the needs of special categories of consumers (RTDS Group, 2014).

3D printing, also known as “additive manufacturing” (AM), is a process that generates freeform structures by introducing a prototype into CAD software; the prototype is then converted by slicing software into a suitable file form that can be recognised and processed by 3D printers (Noorani, 2017). The technology is based on layer-by-layer deposition with predetermined thickness to create complex 3D objects from different materials used like inks; the minimum necessary amount of materials is strictly used to consolidate the shape of the printed objects.

When it comes to food design/manufacturing using 3D printing, three categories were identified as a raw materials, based on the printability of food ingredients (Sun et al., 2015), as follows: (i) native printable food materials (cheese, vegemite and marmite, chocolate) that have enough flow ability to be easily extruded, (ii) non-native printable traditional food materials (meat, fish & seafood, fruits & vegetables) that require addition of flow enhancers to ease the extrusion and post-cooking process, and (iii) alternative ingredients, which are novel sources of functional constituents allowing customisation of nutrition (proteins and fibres isolated from insects, algae, bacteria and fungi (Sun et al., 2015). Meat and meat by-products are non-printable by nature due to their fibrous structures. Therefore, such raw materials require modification of their rheological and mechanical properties via addition of flow enhancers to obtain an extrudable paste-like material (Liu et al., 2018).

In general, 3D printing is considered as a novel technology with broad spectrum of applications in the medical field (tissue engineering), automotive and aerospace fields (component design), fashion,

and lastly, food design (Gross *et al.*, 2014). 3D printing is a relevant technology with sustainable benefits such as reduced demand for raw materials, workforce, energy and transportation (Peng, 2016; Sher & Tuto, 2015). However, some issues still need to be improved and require intensive research and optimisation for 3D printing, such as time consumption for initial inversion, limited printable materials, accuracy level and surface finish (Noorani, 2017).

3D printing of meat is a novel technology that is still undergoing intensive research and needs substantial improvements to comply with technological processes and satisfy consumer demands. The meat safety assurance system will need to be adapted to allow effective control of the process, specifically addressing potential public health issues related to additives which are used to obtain meat in the form of paste-like materials suitable for extrusion.

## Conclusion

The meat industry has undergone substantial changes over the previous several decades due to development of new technologies in primary production and meat processing. The current, traditional meat inspection protocols (ante-mortem and post-mortem), based on visual inspection, palpation and incision, had not been changed since the end of the nineteenth century. Although the traditional inspection approach was effective at the time it was introduced, with regard to detection of classical zoonoses (brucellosis, tuberculosis, cysticercosis, anthrax), it is not fully efficient in terms of the current needs for consumer protection. Namely, public health hazards associated with meat are, nowadays, the zoonotic food (meat) borne pathogens (*Salmonella*, *Campylobacter*, STEC, *Listeria monocytogenes*) that are responsible for the majority

of human illnesses attributed to meat consumption; traditional meat inspection cannot respond effectively to detection of such food borne hazards, but can even increase cross-contamination due to palpation and/or incision procedures. Therefore, there is a need to develop a novel, modern meat inspection system which will be risk- and evidence-based and will cover the farm-chilled carcass continuum — this is the meat safety assurance system or carcass safety assurance system. The risk managers (OV/Official Auxiliary, FBO designated staff/abattoir workers), who are responsible for decision-making within the meat safety assurance system, should decide on the level and type of ante-mortem and post-mortem inspection, based on FCI/HEI. When FCI/HEI reflect high levels of farm biosecurity, animal health and animal welfare, risk managers can decide to apply visual-only inspection, without compromising the meat safety. EFSA recently recommended this approach to the EU MS. The process of introducing and scaling up the meat safety assurance system to full implementation will be gradual, flexible and carefully tuned to avoid unnecessary disruption of meat production chain and to allow stakeholders in the meat chain (farmers, meat processors, competent authorities and consumers) to achieve their public health and economic goals successfully. Lastly, novel technologies to be introduced in livestock chains and meat value chains are in the scope of rearing food producing animals on farm (PLF, sensing systems), slaughter & dressing (automation and robotization) and meat processing (precision fermentation, 3D printing). In the foreseeable future, these novel technologies will also have a disruptive and substantial impact on the meat value chains; this will require further and continuous adaptation or even thorough transformation of the meat safety assurance system to comply with meat safety and consumer protection regulations.

# Bezbednost mesa: Sistem osiguranja baziran na oceni rizika i nove tehnologije

Ivan Nastasijević, Slavica Vesković, Milan Milijašević

**A b s t r a k t:** Industrija mesa je prošla kroz suštinske promene tokom prethodnih nekoliko decenija usled razvoja novih tehnologija u primarnoj proizvodnji (životinje u farmskom uzgoju) — precizan farmski uzgoj, senzorski sistemi; klanje i obrada — automatizacija i robotizacija; i prerada mesa — precizna fermentacija, trodimenzionalno štampanje mesa. Sadašnja, tradicionalna inspekcija mesa (ante-mortem i post-mortem), bazirana na vizuelnom pregledu, palpaciji i inciziji, nije bila promenjena još od kraja devetnaestog veka. Premda je takav tradicionalni pristup bio efektivan u vreme kada je usvojen, u kontekstu detekcije klasičnih zoonoza (bruceloza, tuberkuloza, cisticerkoza, antraks infekcije), on nije u potpunosti efikasan u kontekstu sadašnjih potreba u vezi sa zaštitom potrošača. Naime, opasnosti po javno zdravlje koje potiču od mesa u današnje vreme su povezane sa zoonotskim alimentarnim patogenima (*Salmonella*, *Campylobacter*, Shiga toxin-producing *E. coli*, *Listeria monocytogenes*) koje fekalno izlučuju zdrave životinje, a koji su odgovorni za većinu oboljenja ljudi povezanih sa konzumacijom mesa; tradicionalna inspekcija mesa ne može da odgovori efektivno u vezi sa detekcijom takvih alimentarnih opasnosti, već čak može da dovede i do uvećanja unakrsne kontaminacije mesa usled primene procedura palpacije i incizije. Stoga, postoji potreba da se razvije novi, moderan sistem inspekcije mesa koji će biti baziran na analizi rizika i zasnovan na naučnoj evidenciji — „sistem za osiguranje bezbednosti mesa“ ili „sistem za osiguranje bezbednosti trupa“. Takav moderan sistem treba da bude baziran na upravljanju rizikom i protokolima za inspekciju mesa shodno analizama informacija iz lanca hrane/Harmonizovanih epidemioloških indikatora u kontinuumu farma-ohlađen trup.

**Ključne reči:** bezbednost mesa, sistem osiguranja, inspekcija mesa, automatizacija, kultivisano meso.

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