Content is avaliable at SCOPUS

Meat Technology — Special Issue 64/2

www.meatcon.rs ▪ www.journalmeattechnology.com

UDK: 637.5

ID: 126556937

https://doi.org/10.18485/meattech.2023.64.2.17

Review paper

Challenges in agri-food chain: biosensors in the meat production system

Ivan Nastasijević[a], Ivana Podunavac[b], Saša Janković[a], Radmila Mitrović[a] and Vasa Radonić[b]*

[a] *Institute of Meat Hygiene and Technology, Kaćanskog 13, 11040 Belgrade, Serbia*
[b] *BioSense Institute, University of Novi Sad, 21000 Novi Sad, Serbia*

A R T I C L E I N F O

Keywords:
Agri-food chain
Meat production
Animal health
Animal welfare
Food safety
Biosensors

A B S T R A C T

The complexity of the meat chain is well-known, beginning with the Pre-harvest (feed, farm biosecurity, herd/flock health status, animal welfare, transportation, livestock market/abattoir lairage), followed by Harvest (slaughter, dressing, chilling) and Post-harvest (deboning, meat processing, packaging, distribution, retail, consumer) modules.

Over the previous decade, consumer awareness increased globally towards animal health, animal welfare and food safety issues, including food quality, food fraud, sustainability and climate change impact on meat production. Therefore, consumers demand proper and accurate information on the aforementioned issues in real time for making informed choices when buying their preferred meat/meat products. The transformation of traditional meat value chains towards sustainability needs reliable and affordable tools to optimize such transformation and achieve higher levels of food safety. Sensing systems (biosensors) and their regular use within an integrated meat production chain, from farm-to-fork, can play an important role and be a part of the solution for climate-smart and sustainable agri-food chain considering biosensor function in early and accurate detection of food(meat)-borne pathogens and other food contaminants (residues). The application of biosensors can provide accurate and concentrated data on animal health and welfare, including food borne hazards, to support food safety risk assessment in both, \`traditional\` and \`novel\` (cell-based meat) meat value chains for the benefit of the global population.

1. Introduction

The meat production chain is a highly complex system that involves various stages and stakeholders, beginning with Pre-harvest (feed, farm biosecurity, herd/flock health status, animal welfare, transportation, livestock market/abattoir lairage), followed by Harvest (slaughter, dressing, chilling) and Post-harvest (deboning, meat processing, packaging, distribution, retail, consumer) modules. Over the previous decade, consumer awareness increased globally towards animal health, animal welfare and food safety issues and consumers demand proper and accurate information on the aforementioned issues in real-time for making informed choices when buying their preferred meat/meat products. The meat production system is also facing climate change impacts, recognized as the change of trends of global temperatures, precipitations and wind patterns, that are attributed directly or indirectly to human activity (*UNFCCC*, 1992), with extreme events becoming more frequent, severe and unpredictable. These events may jeopardize food security by influenc-

***Corresponding author:** Ivan Nastasijević, *ivan.nastasijevic@inmes.rs*

Paper received May 16th 2023. Paper accepted May 28th 2023.
Published by Institute of Meat Hygiene and Technology — Belgrade, Serbia

ing various biological contaminants, including food borne hazards, and altering their occurrence, virulence and distribution and increasing the exposure of consumers (*FAO*, 2022). For example, the potential association between rising temperatures and increased levels of antimicrobial resistance (AMR) in certain zoonotic food (meat) borne pathogens has been observed, e.g., *Campylobacter* spp., *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli*. Furthermore, these pathogens are showing increased resistance, in particular, to Critically Important Antibiotics (CIA), reducing the efficacy and quality of clinical treatments (*Poirel et al*., 2018; *Van Puyvelde et al*., 2019; *WHO*, 2019). Another challenge related to the meat chain is its sustainability and environmental impact of the livestock production chain which contributes a certain share to anthropogenic Greenhouse Gas (GHG) emissions (*FAO*, 2022).

Mitigation strategies that include improvement of animal health and welfare can significantly reduce emissions. To achieve that goal, the specificity of livestock production and local production systems should be taken into consideration (*Özkan et al*., 2022). A new challenge is related to the process control of cell-based meat, which is based on culturing cells isolated from animals, followed by processing to produce food products that are comparable to the corresponding animal versions. The potential food safety hazards are associated with cell selection (faecal-borne pathogens), production (*Mycoplasma*), harvesting (biological components, such as growth factors and hormones from animal serum), food processing and formulation (additives, ingredients, nutrients) (*FAO*, 2022b), but can be tackled more efficiently with smart application of biosensors.

2. Biosensor application in the meat chain

Application of biosensors in the farm-abattoir continuum has a wide range of possibilities and can contribute to and provide significant benefits in the optimization of livestock farm management practices.

2.1. Definition and structure of biosensors

A biosensor is a device which recognizes a target biomarker (e.g. pathogen, stress hormone, acute phase protein, viruses, etc.) via an immobilized sensing element called a bioreceptor (monoclonal antibody, RNA, DNA, aptamer, glycan, lectin, enzyme, tissue, whole cell). It has rapid, sensitive and specific detection capabilities. The typical biosensor system consists of a sensing element with bioreceptor and transducer that converts the signal into a corresponding electrical signal suitable for processing and visualization (Figure 1). The choice of biosensor type depends on the targeted biomarker, the nature of the analyte, the desired sensitivity and the intended application.

There are different types of biosensors based on the biological recognition element (bioreceptor) and the transducer used. For example, *electrochemical biosensors*, *piezoelectric biosensors*, *field-effect transistor (FET) biosensors* and *magnetic biosensors*.

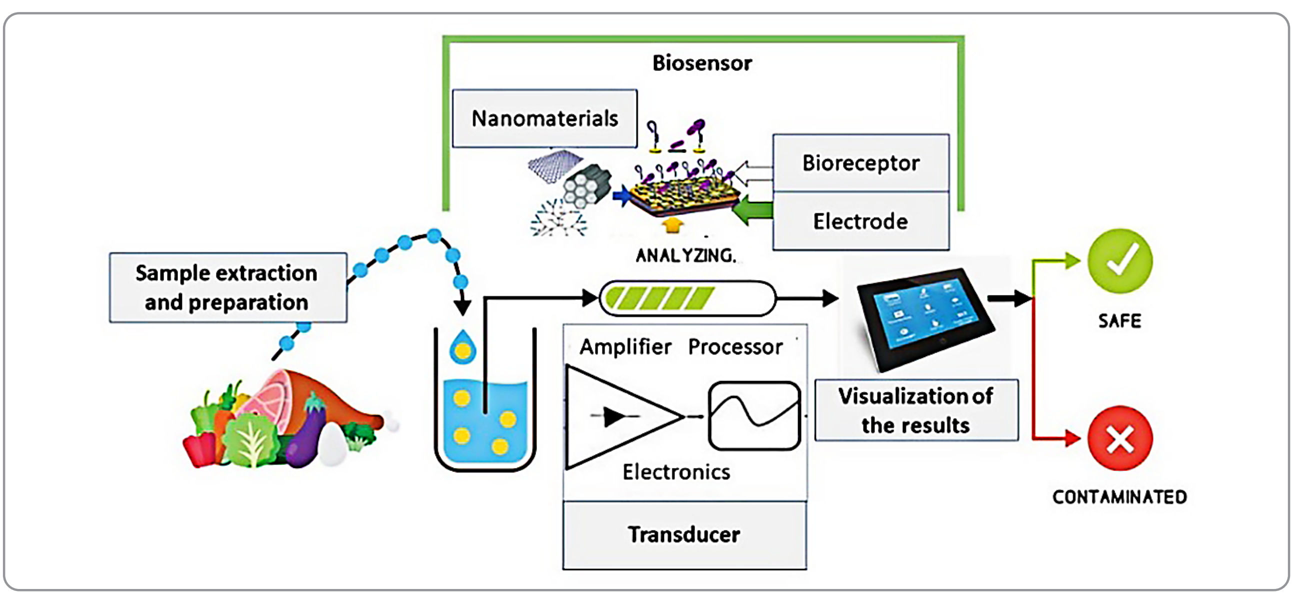

Figure 1. Biosensor with biosensing electrode (bioreceptor) and transducer that convert targeted biosignal to electrical one

2.2. Biosensors application in the farm-abattoir continuum

Biosensors, as point-of-care (PoC) devices, have the potential to detect and quantify physiological, immunological and behavioural responses of livestock and multiple animal species (*Neethirajan et al*., 2017) in the farm-abattoir continuum. They present the lab-on-a-chip concept as an alternative to the commonly used methods such as enzyme-linked immunosorbent assay (ELISA) and/or reverse transcription polymerase chain reaction (RT-PCR) that require adequate environment and space, specifically trained personnel and are time-demanding and more expensive.

2.2.1 Biosensors on the farm

Application of biosensors on-farm has a wide range of technically available opportunities related to behavioural aspects of livestock connected with their feeding dynamics, e.g. *mechanical sensors* (jaw movement) (*Rutter*, 2000) or *acceleration sensors* (feeding behaviour) (*Herinaina et al*., 2016). Furthermore, biosensors able to detect metabolic conditions are available, such as *perspiration metabolite biosensors* (e.g., physical stress via analysis of sweat for sodium and lactate levels) (*Schazmann et al*., 2010), *biosensors for salivary detection of metabolites* (cortisol) (*Yamaguchi et al*., 2013) or *tears analysis biosensors* (glucose sensor) (*La Belle et al*., 2014) or *breath analyses biosensors* (detection of Volatile Organic Compounds — VOCs, e.g. ketosis) (*Leopold et al*., 2014), Bovine Respiratory Diseases (BRD) (*Burciaga-Robles et al*., 2009), brucellosis (*Knobloch et al*., 2009), bovine tuberculosis (*Fend et al*., 2005), Johne`s diseases (*Kumanan et al*., 2009), ketoacidosis (*Mottram et al*., 1999), foot and mouth (FMD) disease (*Christensen et al*., 2011). *Other biosensors* for the detection of animal disease include detection of H7N1 antibodies for Avian Influenza virus (AIV) (*Wang et al*., 2009) or detection of specific acute phase proteins such as biosensor for detection of mastitis (based on haptoglobin detection) (*Martins et al*., 2019). *Biosensors for the detection of stress in fish* also have been developed to respond to stressors (changes in water chemistry, dissolved oxygen content, pH and metal toxicity) associated with water pollution and changes in climate, including behavioural changes (attacking behaviour and visual irritation) (*Wu et al*., 2015a).

2.2.2 Biosensors in the abattoir

The regulatory-based or routine usage of biosensors for the purposes of meat production control and monitoring is not available. However, the recent advancement in design of biosensors enabled rapid and reliable qualitative and quantitative detection of food(meat)borne pathogens, such as lateral flow aptamer-based biosensors for point-of-care detection of *Salmonella enteritidis* and *Escherichia coli* O157:H7 with sensitivity level of 10^1 CFU/ml, respectively (*Fang et al*., 2014; *Wu et al*., 2015b), *Campylobacter* in meat (poultry) samples with detection level of 1.5×10^1 CFU/g (DNA-based sensor) (*Manzano et al*., 2015), toxins of *Clostridium perfringens* (mammalian cell-based sensors) (*Yoo et al*., 2016), *Escherichia coli* (antibody-based or conductometric-based biosensors) at detection levels from 1 to 10^3 CFU/mL (*Jaffrezic-Renault et al*., 2007; *El Ichi et al*., 2014). Biosensors in the abattoir can be also used for environmental control/monitoring of the condition of abattoir wastewater via detection of Biochemical Oxygen Demand (BOD), which is a widely used parameter to describe the level of organic pollution in water and wastewaters (*Chee et al*., 1999). However, the performance of biosensors in the farm-abattoir continuum is constrained *in vitro* with the enriched bacterial suspensions encountered, and there is scarcity of data regarding the matrix (e.g. straw, faeces, blood) from the real operational environment (farm, abattoir), which requires further and deeper research.

2.3. Biosensors, meat production and climate change

Livestock is a potential climate change driver, generating up to 14.5% of total anthropogenic GHG emissions (*Cheng et al*., 2022). The conclusions drawn from similar studies should be taken with precaution, having in mind that these studies mainly considered the intensive farming livestock production systems and not extensive systems (e.g., rotational grazing system), which might even have a positive environmental impact by allowing vegetation to recover and reducing gas emissions via enhancing carbon storage and reducing the need for intensive feed production. Biosensing technology, integrated in precision livestock farming, can be an important tool in monitoring solutions for reduction of GHG emissions that originate from intensive livestock farming and, thus, facilitating the climate change mitigation, including environmental and agricultural sustainability (*Griesche and Baeumner*, 2020; *Wang et al*., 2022). This type of biosensor technology should become the key component of climate-smart agriculture and "4th revolution" in the agri-food chain (*FAO*, 2015).

2.4. Biosensors and cell-based meat

The in-line monitoring of the bio-process of meat cultivation in bioreactors can improve the efficiency and consistency of cell-based (`cultured` or `cultivated` or `clean`) meat production. Recently, cell-based food production (growing animal-based agricultural products directly from cell cultures), has been explored as a sustainable alternative to the conventional livestock and food of animal origin system, to satisfy the needs of increasing global demand for animal-source protein (*OECD-FAO*, 2022; *FAO/WHO*, 2023). The prototype biosensors are under development to enable in-situ measurements of biomass, nutrient and metabolite quantities in specific growth media (*Good Food Institute*, 2020).

3. Conclusions

The regular and routine introduction of biosensors can facilitate the transformation of the whole food (meat) value chain `from farm to fork` (via advanced Food Chain Information flow in the farm-abattoir continuum), by enabling continuous monitoring and/or early detection of animal disease and food safety hazards, so providing more sustainable and climate-friendly meat production, by reducing GHG emissions (via optimized nutrition, animal health and welfare), and by reduction of food waste.

Disclosure statement: No potential conflict of interest was reported by the authors.

Funding: This work was supported by Technology Transfer Programme of the Innovation Fund, Republic of Serbia within the project "Development and Integration of Multiplex Microfluidic Biosensors for Meat Safety monitoring in farm-to-slaughterhouse continuum (DIBMES)" [Grant Agreement TTP 1125] & programme `IDEAS` of the Science Fund, Republic of Serbia, project "Microfluidic Lab-on-a-Chip platform for fast detection of pathogenic bacteria using novel electrochemical aptamer-based biosensors (MicroLabAptaSense)" [Grant Agreement No. 7750276].

References

Burciaga-Robles, L. O., Holland, B. P., Step, D. I., Krehbiel, C. R., McMillen, G. I., Richards, C. J., Sims, L. E., Jeffers, J. D., Namjou, K. & McCann, P. J. (2009). Evaluation of breath biomarkers and serum haptoglobin concentration for diagnosis of bovine respiratory disease in heifers newly arrived at a feedlot. *American Journal of Veterinary Research*, 70(10), 1291–1298.

Chee, G.-J., Nomura, Y., Ikebukuro, K. & Karube, I. (1999). Development of highly sensitive BOD sensor and its evaluation using preozonation. *Analaltical Chimica Acta,* 394, 65–71.

Cheng, M., McCarl, B. & Fei, C. (2022). Climate Change and Livestock Production: A Literature Review. *Atmosphere,* 13, 140, https:// doi.org/10.3390/atmos13010140

Cho, I.-H., Kim, D.H. & Park, S. (2020). Electrochemical biosensors: perspective on functional nanomaterials for on-site analysis. *Biomaterials Research,* 24(6), https://doi.org/10.1186/s40824-019-0181-y

Christensen, L. S., Brehm, K. E., Skov, J., Harlow, K.W., Christensen, J. & Haas, B. (2011). Detection of foot-and-mouth disease virus in the breath of infected cattle using a hand-held device to collect aerosols. *Journal of Virolsology Methods*, 177(1), 44–48.

El Ichi, S., Leon, F. & Vossier, L. et al. (2014). Microconductometric immunosensor for label-free and sensitive detection of gram-negative bacteria. *Biosens Bioelectron*, 54, 378–384.

Fang, Z., Wu, W., Lu, X. & Zeng, L. (2014). Lateral flow biosensor for DNA extraction-free detection of *Salmonella* based on aptamer mediated strand displacement amplification. *Biosens Bioelectron*, 56, 192–197.

FAO/WHO, (2023). *Food safety aspects of cell-based food,* https://www.fao.org/3/cc4855en/cc4855en.pdf (accessed on 11 May 2023).

FAO, (2022). Thinking about the future of food safety. A foresight report. Rome, https://www.fao.org/3/cb8667en/cb8667en (accessed on 27 April 2023).

FAO, (2022b). *Food safety aspects of cell-based food — Background document two: Generic production process.* Rome, https://www.fao.org/3/cc2502en/cc2502en.pdf (accessed on 27 April 2023).

FAO, (2015). Climate Smart Agriculture Sourcebook, https://www.fao.org/climate-smart-agriculture-sourcebook/en/ (accessed on 10 May 2023).

Fend, R., Geddes, R., Lesellier, S., Vordermeier, H.-M., Corner, L. A. L., Gormley, E., Costello, E., Hewinson, R. G., Marlin, D. J., Woodman, A. C. & Chambers, M. A. (2005). Use of an electric nose to Diagnose *Mycobacterium* *bovis* infection in badgers and cattle. *Journal of Clinical Microbiology,* 43(4), 1745–1751.

Good Food Institute, (2020). Real Sense: Integrating biosensors for cultivated meat, https://gfi.org/researchgrants/realsense-integrating-biosensors-for-cultivated-meat/ (accessed on 11 May 2023).

Griesche, C. & Baeumner, A. J. (2020). Biosensors to support sustainable agriculture and food safety. *TrAC Trends in Analytical Chemistry* 128, 115906.

Herinaina, A. I., Bindelle, J., Mercatoris, B. & Lebeau, F. (2016). A review on the use of sensors to monitor cattle jaw movements and behaviour when grazing. *Biotechnology Agronomy Sociology and Environment,* 23(S1), 273–286.

Jaffrezic-Renault, N., Martelet, C., Chevolot, Y. & Cloarec, J. P. (2007). Biosensors and bio-bar code assays based on biofunctionalized magnetic microbeads. *Sensors*, 7, 589–614.

Knobloch, H., Kohler, H., Commander, N., Reinhold, P., Turner, C., Chambers, M., Pardo, M. & Sberveglieri, G. (2009). Volatile organic compounds (VOC) analysis for disease detection: proof of principle for field studies detecting paratuberculosis and brucellosis. AIP Conference Proceedings, 195–197.

Kumanan, V., Nugen, S.R., Baeumner, A. J. & Chang, Y.-F. (2009). A biosensor assay for the detection of *Mycobacterium avium subsp. paratuberculosis* in fecal samples. *Journal of Veterinary Science*, 10(1), 35–42.

La Belle, J. T., Engelschall, E., Lan, K., Shah, P., Saez, N., Maxwell, S., Adamson, T., Abon-Eid, M., McAferty, K., Patel, D. R. & Cook, C. B. (2014). A disposable tear glucose biosensor-part 4: preliminary animal model study assessing efficacy, safety, and feasibility. *Journal of Diabetes Science and Technology*, 8(1), 109–116.

Leopold, J. H., van Hooijdonk, R. T., Sterk, P. J., Abu-Hanna, A., Schultz, M. J. & Bos, L. D. (2014). Glucose prediction by analyses of exhaled metabolites — a systematic review. *BMS Anesthesiology*, 14, 46.

Manzano, M., Cecchini, F. & Fontanot, M. et al. (2015). OLED-based DNA biochip for *Campylobacter* spp. detection in poultry meat samples. *Biosens Bioelectrony*, 66, 271–276.

Martins, S. A. M., Martins, V. C., Cardoso, F. A., Germano, J., Rodrigues, M., Duarte, C., Bexiga, R., Cardoso, S. & Freitas, P. P. (2019). Biosensors for On-Farm Diagnosis of Mastitis. *Frontiers in Bioengineering and Biotechnology*, 7, 186, 1–19.

Mottram, T., Dobbelaar, P., Schukken, Y., Hobbs, P. & Bartlett, P. (1999). An experiment to determine the feasibility of automatically detecting hyperketonaemia in dairy cows. *Livestock Production Science*, 61(1), 7–11.

Neethirajan, S., Tuteja, S. K., Huang, S.-T. & Kelton, D. (2017). Recent advancement in biosensors technology for animal and livestock health management. *Biosensors and Bioelectronics*, 98, 398–407.

OECD-FAO, (2022). Agricultural Outlook 2022–2031, Chapter 6. Meat, https://doi.org/10.1787/f1b0b29c-en (accessed on 11 may 2023)

Özkan, Ş., Teillard, F., Lindsay, B., Montgomery, H., Rota, A., Gerber P., Dhingra M. & Mottet, A. (2022). The role of animal health in national climate commitments. Rome, FAO, https://doi.org/10.4060/cc0431en. file:///C:/Users/Ivan/Downloads/cc0431en.pdf (accessed on 19 April 2023).

Poirel, L., Madec, J.Y., Lupo, A., Schink, A. K., Kieffer, N., Nordmann, P. & Schwarz, S. (2018). Antimicrobial Resistance in *Escherichia coli*. Microbiology Spectrum, 6(4), https://doi: 10.1128/microbiolspec.ARBA-0026-2017

Rutter, S. M. (2000). Graze: a program to analyze recordings of the jaw movements of ruminants. *Behavior Research Methods, Instruments & Computers*, 32(1), 86–92.

Schazmann, B., Morris, D., Slater, C., Beirne, S., Fay, C., Reuveny, R., Moyna, N. & Diamond, D. (2010). A wearable electrochemical sensor for the real-time measurement of sweat sodium concentration. *Analalitical Methods* 2(4), 342–348.

UNFCCC, (1992). United Nations Framework Convention on Climate Change, https://unfccc.int/resource/docs/convkp/conveng.pdf (accessed on 24 April 2023).

Van Puyvelde, S., Pickard, D. & Vandelannoote, K. et al. (2019). An African *Salmonella Typhimurium* ST313 sublineage with extensive drug-resistance and signatures of host adaptation. *Natural Communication*, 10, 4280.

Laca, E. A. & Wallis De Wries, M. (2001). Acoustic measurement of intake and grazing behaviour of cattle. *Grass Forage Science*, 55(2), 97–104.

Wang, R., Wang, Y., Lassiter, K., Li, Y., Hargis, B., Tung, S., Berghman, L. & Bottje, W. (2009). Interdigitated array microelectrode based impedance immunosensor for detection of avian influenza virus H5N1. *Talanta,* 79(2), 159–164.

Wang, X., Luo, Y., Huang, K. & Cheng, N. (2022). Biosensor for agriculture and food safety: Recent advances and future perspectives. *Advanced Agrochemistry*, 1(1), 3–6.

WHO, (2019). Critically Important Antimicrobials for human medicine : 6th Revision. Ranking of medically important antimicrobials for risk management of antimicrobial resistance due to non-human use, https://www.who.int/publications/i/item/9789241515528 (accessed on 25 April 2023).

Wu, H., Aoki, A., Arimoto, T., Nakano, T., Ohnuki, H., Murata, M., Ren, H. & Endo, H. (2015a). Fish stress become visible: A new attempt to use biosensor for real-time monitoring fish stress. *Biosensors and Bioelectronics*, 67, 503–510.

Wu, W., Zhao, S., Mao, Y., Fang, Z., Lu, X. & Zeng, L. (2015b). A sensitive lateral flow biosensor for *Escherichia coli* O157:H7 detection based on aptamer mediated strand displacement amplification. *Analytica Chimica Acta*, 861, 62–68.

Yamaguchi, M., Matsuda, Y., Sasaki, S., Sasaki, M., Kadoma, Y., Imai, Y., Niwa, D. & Shetty, V. (2013). Immunosensor with fluid control mechanism for salivary cortisol analysis. *Biosens Bioelectron*, 41, 186–191.

Yoo, S. M. & Lee, S. Y. (2016). Optical biosensors for the detection of pathogenic microorganisms. *Trends in Biotechnology*, 34, 7–25.