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DIGITAL MONITORING SYSTEMS IN THE FOOD INDUSTRY: A REVOLUTION IN QUALITY AND EFFICIENCY

Ramona-Raluca STOIA, Marius MIHUT, Anca DRAGHICI

Abstract: *The growing concerns about the increase in population necessitate modern technologies to increase the productivity in the food industry and support the new challenges of food safety and quality (FSQ) risks. The paper aims to discuss the application of digital monitoring systems (DMS) in the food industry, highlighting the integration of emergent technologies (e.g., Artificial Intelligence (AI), Internet of Things (IoT), blockchain, big data analytics etc.). These technologies enhance real-time monitoring, traceability, and control throughout the entire food supply chain, ensuring high standards of FSQ. Finally, there is presented the digital monitoring system development approach and generic architecture, considering the main characteristics and solutions present in the literature and in practice (based on the legal framework in Europe and stakeholders' involvement).*

Keywords: *Food safety and quality (FSQ), digitalization, food industry, sustainability, Industry 4.0, innovation, process optimization.*

1. INTRODUCTION

The actual phenomena of global warming due to climate changes, accompanied by population growth phenomena and the rise of food waste and loss have impacted food safety and quality (FSQ) risks management related to new diseases or pandemic outbreaks. Thus, new challenges that threaten future food sustainability and negatively affect public health urgently need to be addressed with modern technologies as the digital one are [1].

There have been observed that "the Food Industry 4.0 Era has been characterized by new challenges, opportunities, and trends that have re-shaped current strategies and prospects for food production and consumption patterns, paving the way for the move toward Industry 5.0" [2].

The paper presents an overview of the research trends of the digitalization of FSQ processes developing the basis for the presentation of digital monitoring systems (DMS) in the food industry. This is considered as a revolution in quality and efficiency management. On the one hand, the research findings (based on the literature review, analysis and synthesis of the most relevant studies in the field) try to fill the knowledge gap in the field.

In addition, from a practical point of view, there is a lack of rapid identification of risks and unsafe or potentially unsafe foods so that they can be withdrawn from the market as quickly and efficiently as possible. Digital technologies in FSQ can improve the system's reaction and risk management processes. On the other hand, the functionalities needed for DMS in the food industry will be presented, with technologies that are already in use in different manufacturing and logistics systems in the food industry.

Thus, the paper presents a literature overview for defining and characterizing the state of digitalization in the food industry for increasing FSQ.

The paper's structure consists of four parts as follows: (a) Literature review and research trends in FSQ; (b) A synthesis of the legal framework in the European Union together with a stakeholders' mapping in FSQ areas; (c) Mapping the main stakeholders in the FSQ; (d) Presentation of the problems, characteristics and solutions for DMS are transforming the food industry. Finally, conclusions and future research will be formulated.

2. LITERATURE REVIEW

Digital technologies are revolutionizing the field of FSQ by enhancing monitoring, traceability, and control throughout the entire food supply chain. These technologies, including AI, IoT, blockchain technologies, big data, data analytics, data mining, and different type of sensors, can provide real-time data and insights that help in early detection of potential hazards, ensuring transparency and efficiency. As is evident in recent literature, the digitalization of processes through the integration of new and emerging technologies can lead to a high level of FSQ [2-8]. Table 1 presents a synthesis and analysis of the most representative articles in the field of investigation, highlighting the results obtained and the methodologies by which they were generated.

Table 1

Key aspects in the FSQ knowledge field (literature review).

Article	Insights	Research methodology used
[1]	The study highlighted the progress and rapid dynamics of digital technologies used in the field of FSQ. Thus, using robotics, digital twins, computer vision, AI and data analysis (big data) for the growth of FSQ can be effective and efficient practices in the food industry. These types of technologies have been implemented in the case of raw material sorting processes, in the evaluation and optimization/improvement of product quality. Specialized software applications are already used in the automation of industrial processes and in FSQ, considering the logistics chain (from raw materials to final sale). The focus of the study was on applying non-thermal "processing, with optimization of processing (sensors, IoT, big data, AI)" in the case of food industry.	Literature review of the main digital "technologies that are implemented in the food industry"; Examples and best practices of digital technologies implemented and used in the food industry; "SWOT analysis for Food Industry 4.0".
[3]	The study is developed in the context of ensuring public health through FSQ. It is highlighted that digital technologies used in the FSQ field are applied to "real-time monitoring processes, traceability and quality control throughout the supply chain". The technologies analyzed are AI, IoT, blockchain, Big Data, robotics and smart sensors which are used for improving risk management, transparency and predictive modeling. The study highlights the importance of adopting these technologies to maintain global food safety standards. The study demonstrates that digital technologies implementation "improve productivity, reduce food safety risks, and enhance the sustainability of the entire supply chain".	Literature review of the main digital technologies that are already implemented in agri-food processing, referring to FSQ aspects; Case studies of digital technologies implemented and used in agricultural-food processing are shown; Trends are estimated and discussed, as conclusions of the literature review (discussion are in the context of Agriculture 4.0 and sustainable development goal 12).
[4]	The literature review analyzed the use of Machine-learning (ML) with AI technologies for FSQ; it was demonstrated how AI and ML were able to provide quick and creative answers to improve FSQ. The research included a presentation of AI and ML technologies used and applied in FSQ, an inventory of challenges and key aspects to be considered in the application of ML with AI in different stages of agricultural food processing (table syntheses). Authors proposed and developed the "flowchart of applications of AI and ML in various stages of agri-food processing".	The presented bibliographic synthesis is based on a methodology that considered the extraction of valuable information from the most relevant and authoritative articles published until 2022, using the databases: PubMed, IEEE Xplore and ScienceDirect.
[5]	The study is developed in the context of the United Nations' Sustainable Development Goal 12 (SDG 12) and "Target 12.3 to foster responsible consumption and production patterns and to halve per capita food waste respectively by 2030". The debate balances between the digital agricultural technologies' implementation and the environmental sustainability. Despite the potential of digital technologies (e.g., GPS, RFID, and digital simulations) to prevent or reduce food waste, the study mentions	Literature review of the food system consists of "all elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of

	that the complicated design of automation and mechanization solutions can lead to inefficiency or even damage to food products, in some cases of faulty operation. "The review findings demonstrate that prohibitive investment costs and the digital divide between technology adaptors limit the wide uptake of digital agricultural technologies".	food, and the outputs of these activities, including socio-economic and environmental outcomes"
[6]	"The study aims to analyze and characterize AI applications in the food industry, supply chain management, production, sensory science and personalized nutrition; aspects regarding the use and implementation of knowledge-based expert systems, fuzzy logic, artificial neural networks and machine learning are discussed, highlighting their roles in quality prediction and control, product development and waste management". There has been discussion on the risks and problems in applying AI technologies in the food industry (e.g., data security, ethics, standardization, high costs etc.)	Literature review based on articles from 2020 since 2024 (most of them); The analysis of patents from the post pandemic period; Case studies are used to support the findings in the literature.
[7]	The study presents and classifies biosensors used in the food industry, demonstrating their use with the help of ML (the study includes the presentation of the main ML algorithms applied in food safety field). Several detection devices based on biosensors and machine learning (different types) applied in the FSQ field were presented.	Literature review (most of the articles over 2020); Analysis of "the combined application of biosensors in food safety with the discussion of the limitations and possible solutions"; Estimations of trends in biosensor and ML research.

As can be seen from the analysis included in Table 1, the integration of digital technologies is recognized as being meritorious and with real advantages in the FSQ field. While digital technologies offer significant advancements in FSQ, challenges remain in their integration and standardization across the industry. Future research and development are needed to address these challenges and fully harness the potential of these technologies in ensuring global food safety standards [3, 5, 7].

Summarizing the above state-of-the-art on the research about the digital, emergent technologies used in FSQ, there have been identified the following key objectives [2-6]:

- Enhancing traceability can be assured by digital technologies which enable better "tracking of food products throughout the supply chain", allowing for quick identification of sources in case of contamination;
- Improving monitoring by using IoT devices and sensors "can provide real-time monitoring of environmental conditions, such as temperature and humidity", supporting food store and transport under safe conditions";
- Data-driven decision making based on AI applications that facilitate the analysis of large datasets, helping stakeholders make informed decisions regarding food safety protocols and risk management;
- Increasing efficiency with automation and robotics streamline processes in food production and packaging, and thus, reducing human error and improving overall efficiency;
- Enhancing compliance can be supported by digital tools which help businesses comply with food safety regulations by providing necessary documentation and monitoring compliance in real-time.
- Consumer transparency which can be assured by digital technologies that enable consumers to access information about food origins, safety practices, and ingredient sourcing;
- Predicting risks based on AI and ML technologies that can identify trends and patterns predicting potential safety risks.

In addition, research and industry experience have demonstrated significant benefits of DMS for food safety [2, 4, 5, 6]:

- Improved product safety by reducing contamination and spoilage risks, ensuring safer products for consumers;
- Enhanced process efficiency by optimizing resource utilization and improved production throughput;

- Increased traceability which is related to better tracking of products and ingredients in the logistics chain and in the production field, too;
- Early warning system using proactive identification of potential issues before they lead to product contamination or recalls;
- Technologies contribute to a safer food supply, reducing the risk of foodborne illnesses and enhancing consumer confidence.

3 SYNTHESIS OF THE LEGAL FRAMEWORK AND THE STAKEHOLDERS IN THE EUROPEAN UNION

3.1 Overview of the legal framework

Food legislation pursues one or more objectives general regarding “a high level of protection of life and health human rights and the protection of consumer interests, including practices correct in the food trade”, considering when it is the case, “the protection of animal health and welfare, plant health and the environment”. The main laws governing FSQ in Europe are primarily structured around the General Food Law Regulation (GFLR, [9]) and the Official Controls Regulation, which form the backbone of the EU's food safety framework [10]. These laws are designed to ensure “a high level of protection for human health and consumers' interests, while also facilitating the smooth functioning of the internal market”. In the following will be detailed the key components and principles of these regulations.

GFLR serves as the overarching framework for all EU secondary food laws, establishing principles such as science-based risk analysis, precautionary principles, transparency, and consumer protection; GFLR outlines the responsibilities of Food Business Operators (FBOs) in ensuring food safety. In addition, GFLR regulates the European Food Safety Authority (EFSA) which introduces the Rapid Alert System and Crisis Management procedures to handle food safety emergencies [11].

The Official Controls Regulation (OCR) complements the GFLR by establishing procedures for “official controls to verify compliance with food and feed law, animal health and welfare rules”. It ensures that food safety standards are applied consistently across the EU, thereby maintaining consumer confidence and market integrity. In addition, the food law acquis comprises various specific laws related to food technology, safety, information, quality and nutrition, reflecting the multidimensional nature of EU food law [11]. These laws are harmonized to balance the interests of food producers and consumers, also considering international market dynamics [12].

Food safety legislation at the European Union level has evolved towards priority given to food safety (FSQ), transparency and sustainability [11]. The integration of ethical considerations and consumer awareness has led to increased attention to production processes and product traceability [12]. Although EU FSQ laws are comprehensive, they “continue to evolve in response to new challenges and consumer expectations”; the focus is on sustainability and integrated regulation of the food system [11].

EU FSQ regulations significantly impact the food supply chain by setting strict compliance requirements, improving quality assurance and influencing logistics operations. Thus, the GFLR and OCR form the “backbone” of EU food law enforcement and require all food operators to comply with FSQ standards and empower Member States to carry out official controls and impose sanctions for non-compliance. Furthermore, improved market surveillance complements these regulations by providing proactive measures to prevent FSQ incidents [11].

The EU FSQ legislation includes the regulation of food-borne pathogens, with reference to the entire food supply chain. Prevention and control measures aim to mitigate the risks associated with pathogens (e.g., Salmonella, Listeria, etc.) that can cause consumer illness and disrupt supply chains [13]. Quality labels such as Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) serve for the quality guarantee and product authenticity, influencing consumer confidence and marketability [11].

The implications for the logistics sector in the food industry should not be forgotten, with EU

regulations requiring advanced systems to ensure FSD standards compliance; legislative provisions have the role of preventing supply chain disruptions.

Geopolitical and environmental factors introduce uncontrollable variables into the logistics chain, increasing risks and uncertainties, which requires the search and implementation of innovative solutions such as the Delivered at Frontier (DAF) system to increase supply chain resilience [14]. However, these regulations can pose challenges for smaller businesses that may struggle with compliance costs and logistical demands, highlighting the need for supportive measures to aid these entities in adapting to regulatory requirements.

3.2. Stakeholders mapping in the field of FSQ

The deep understanding of the need and the opportunity to introduce digitization systems in the monitoring of FSQ must consider the interests and needs of the different stakeholders. In general, the main stakeholders in the FSQ field include the categories described in Figure 1. These stakeholders play an important role in supporting the FSQ. Usually, when developing the stakeholders' inventory, it is useful to take into consideration "grey literature" sources as consulting companies reports, organizations' web pages and other reports and studies which have only informative and diagnosis value on the food industry. Based on these information and knowledge sources, there have been several observations provided as in the following.

"Consumer concern over food safety highlights potential for digital assurance". According to [15, 16], the topic is at the top of the agenda for consumers.

Regulating FSQ highlights the importance of measures in preventing foodborne diseases, "extending product shelf-life, enhancing traceability, and reducing food loss and waste". Key interventions and effective measures which are of great interest include [17, 18]:

- Promoting research and development in food monitoring technologies like smart packaging and sensors;
- Adopting food safety regulations to minimize risks from harmful chemical substances and unsafe agricultural inputs;
- Implementing national food control strategies to ensure coherence and efficiency in food safety measures;
- Enhancing food quality through zoning laws, food labels, and certification systems;
- Strengthening the capacity of producers and consumers with better food processing methods and training programs;
- Utilizing technology and collaboration to improve food safety monitoring and communication.

Fig. 1. The main stakeholders in the field of FSQ.

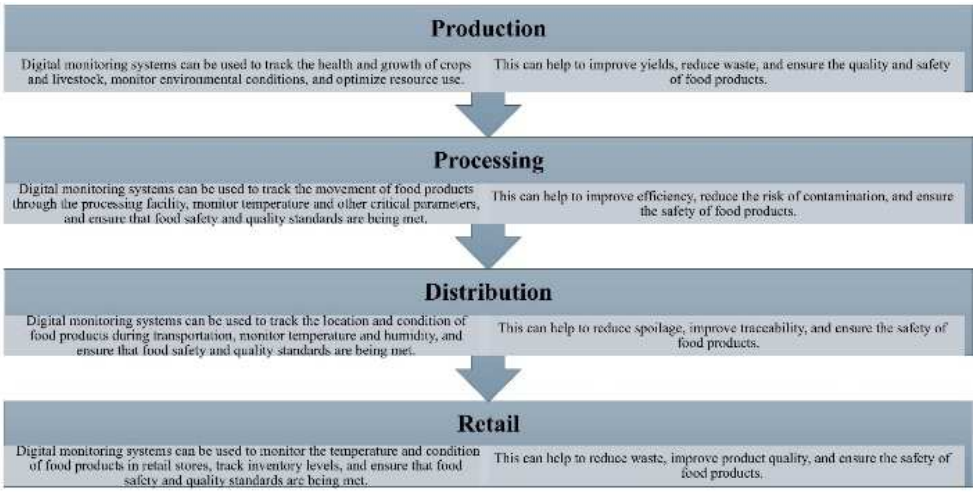

Fig. 2. Overview of the standards in the different ICS fields (synthesis of [22]).

Table 2

Key areas of the research in the field of FSQ (synthesis of [23-27]).

Area	Characteristics	Insights from studies in actual references
Microbiological Safety	This area focuses on identifying and studying foodborne pathogens, such as bacteria, viruses, and parasites, which can cause illness. Areas of interest for research are "biological hazards; foodborne zoonotic diseases; monitoring of foodborne diseases" [23].	Researchers investigate how these pathogens grow and survive in different food environments, as well as how to prevent their contamination [24].
Chemical Safety	This area focuses on the potential hazards posed by chemical contaminants in food, such as pesticides, heavy metals, and toxins. Related topics are "acrylamide; aflatoxins in food; brominated flame retardants; dioxins and PCBs; metals as contaminants in food; mineral oil hydrocarbons; mycotoxins"; per- and polyfluoroalkyl substances (PFAS); process contaminants [23].	Researchers study the sources of these contaminants, their effects on human health, and methods to minimize their presence in food [25].
Food Preservation	This area explores various techniques to preserve "food and extend its shelf life while maintaining its safety and quality" [26].	Researchers investigate the effectiveness of traditional methods like canning and fermentation, as well as newer technologies like irradiation and modified atmosphere packaging [26].
Detection and Prevention	This area focuses on developing new technologies and methods to detect foodborne pathogens and contaminants quickly and accurately [27].	Researchers also work on strategies to prevent contamination "throughout the entire food supply chain, from farm to table" [27].

4. DMS FOR FSQ – THE RESEARCH PROBLEM AND SOLUTIONS

DMS are transforming the food industry, bringing about a revolution in quality and efficiency [19]. "These systems utilize sensors, software, and data analytics to track critical parameters like temperature, humidity, and environmental conditions throughout the food supply chain" [20]. The real-time data provides valuable insights into potential risks, enabling proactive interventions to prevent foodborne illnesses, reducing waste, and ensure FSQ [21]. The field of application for DMS in the food industry is broad and encompasses the entire food supply chain as shown in Figure 2 [22].

As has been discussed in the previous chapters, FSQ research is critical and plays an essential role in protecting public health; it involves studying and monitoring various aspects of FSQ, including the growth of pathogens in food, the effectiveness of different preservation methods, and the development of new technologies to detect and prevent contamination. In researching food quality, we must focus on the aspects presented and briefly characterized in Table 2. Optimizing food processing and storage conditions for new

products in food industry is a complex process that involves more than just creating a "tasty new treat or experience" [1-7, 20-27]. According to the areas of research presented in Table 2, several aspects should be considered [1-8, 20-27]:

- Understanding the product's microbiology - Before a new food product hits the shelves, researchers need to understand its microbial profile. This means identifying any potential pathogens that could grow in the product and determining the factors that influence their growth, such as temperature, pH, and water activity etc.;
- Evaluating preservation methods - Once the microbial risks are understood, researchers can evaluate different preservation methods to ensure the product remains safe throughout its intended shelf life. This might involve testing various techniques like heat treatment, modified atmosphere packaging, or the use of preservatives;
- Determining optimal processing conditions - The processing conditions used to manufacture a food product can significantly impact its safety. Researchers work to identify the optimal combination of time, temperature, and other factors to eliminate harmful microorganisms while preserving the product's quality and nutritional value;
- Assessing packaging and storage - The type of packaging and storage conditions can also affect a product's safety;
- Shelf-life studies - Finally, researchers conduct shelf-life studies to determine how long a product remains safe and of acceptable quality under various storage conditions. This information is crucial for determining the product's expiration date and providing consumers with safe handling instructions.

Food safety research is a continuous process, as new challenges and threats to food safety emerge regularly. Thus, defining the research methodology for implementing DMS should take into consideration this fact (Figure 3). By staying at the forefront of scientific knowledge, researchers can help ensure the safety of the food we consume.

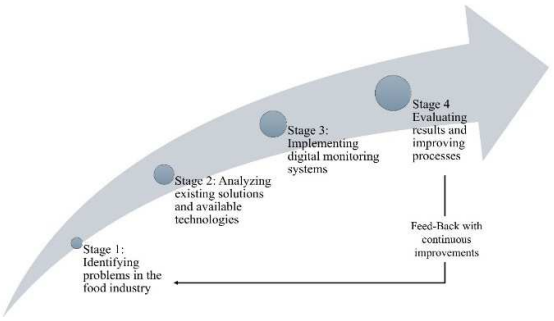

Fig. 3. Overview of the research methodology for implementing DMS.

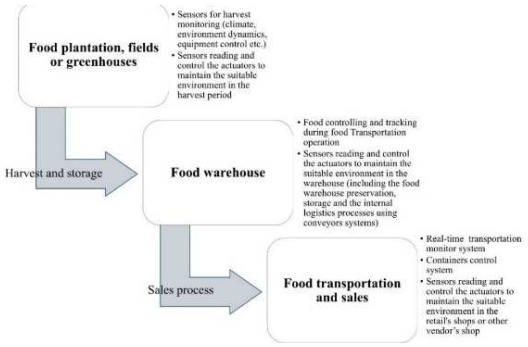

Fig. 4. The generic architecture for DMS.

Furthermore, based on these preliminary considerations, the generic architecture for DMS has been designed extended to an intelligent food supply chain management system (Figure 4). DMS are revolutionizing the food industry, offering unprecedented levels of quality control and efficiency. Here are some of the key methods and tools used in these systems considered in the architecture for DMS [28-30]: temperature monitoring, humidity monitoring, pH monitoring, equipment monitoring; data analytics, alert and traceability systems.

As supported by the research described in [31], there can be considered that the proposed architecture for DMS described in Figure 4, should be designed as an Intelligent Food Assurance System (IFAS based on AI and ML) that could "have the ability to use intelligent sensors, data processing systems and other advanced technologies to detect and control the quality and safety of food" [31]. Also, recent studies [31-34] provide a holistic view of the transformative role of AI and ML in supporting FSQ aspects in the food industry [31-34]. A synthesis is presented in Figure 5.

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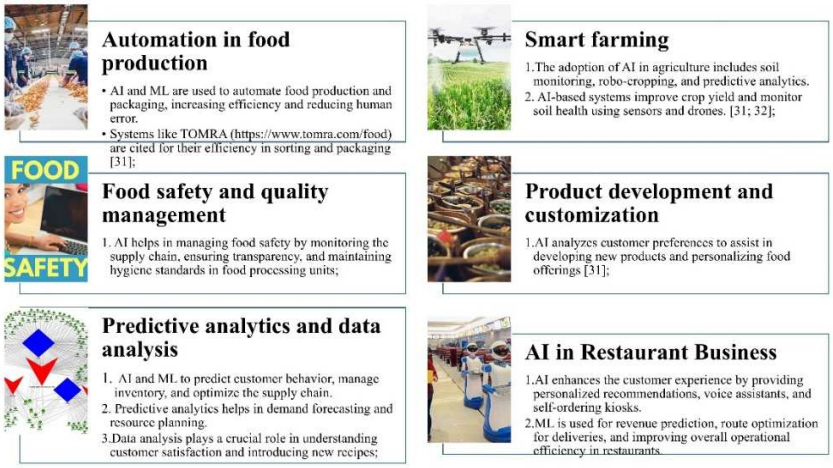

Fig. 5. An overview of the transformative role of AI and ML technologies in the food industry.

5. CONCLUSIONS

The presented bibliographic analysis on the process and formulas of digitalization of processes in the food industry, the analysis of the legislative framework and the presented aspects regarding stakeholder management had the role of characterizing the business ecosystem of the food industry and sublimating the current specificity of the FSQ field

As can be seen, the digitalization of food industry processes and FSQ systems are present and described in actual reference, the debates being focused on the use of technologies such as: IoT, digital twins, computer vision, AI, ML, data analysis, big data, etc. Thus, it can be stated that the adoption and implementation of these emerging technologies, food industry processes improve their traceability, can ensure the obtaining of quality products, can ensure more efficient risk management, and finally, supply chains can be optimized. The costs of implementing such solutions remain high, although there are studies that describe solutions achieved with lower costs. As a result of the literature review and analysis, it can be stated that the future of FSQ is a digital one!

Furthermore, the bibliographic research carried out allows the design of an approach for introducing a DMS (as a general methodology) and a generic architecture of this system was proposed, because it must ensure the creation of an intelligent food supply chain management system.

Future research will be directed towards the definition and complete description of digital monitoring system. Furthermore, developments will consider the specifics of AI use in the FSQ field, which will allow the tracking of outcome indicators in different implementation contexts, through data analysis, big data and, an accurate forecast of the yield and optimization of FSQ [33]. In addition, consideration will be given to the development of indicators measuring "system resilience" that consider its capacity to withstand, adapt and recover from various risks and challenges, resulting from processes and interferences in the FSQ field [34]. By increasing the resilience of systems, we believe that future studies should aim to ensure FSQ, by simultaneously protecting public health and maintaining consumer confidence.

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Sisteme de monitorizare digitală în industria alimentară: o revoluție în calitate și eficiență

Preocupările tot mai mari cu privire la încălzirea globală, creșterea populației și risipa alimentară necesită tehnologii moderne pentru a aborda riscurile legate de calitatea și siguranța alimentelor. Această lucrare își propune să discute despre sistemele digitale de monitorizare în industria alimentară, evidențiind integrarea tehnologiilor avansate precum Inteligența Artificială (AI), Internetul lucrurilor (IoT), blockchain-ul și analiza datelor. Aceste tehnologii îmbunătățesc monitorizarea în timp real, trasabilitatea și controlul de-a lungul lanțului de aprovizionare cu alimente, asigurând standarde înalte de calitate și siguranță a alimentelor. Studiul subliniază importanța digitalizării în automatizarea proceselor, reducerea erorilor umane și optimizarea resurselor. De asemenea, este analizat cadrul legal din Uniunea Europeană și este prezentat inventarul stakeholderilor implicați. În final, este prezentată abordarea dezvoltării sistemului de monitorizare digitală și o arhitectură generică a acestuia, având în vedere principalele caracteristici și soluții prezente în literatură și în practică.

Cuvinte cheie: *Siguranța și calitatea alimentelor (FSQ), digitalizare, industria alimentară, sustenabilitate, Industria 4.0, inovație, optimizarea proceselor.*

Ramona-Raluca STOIA, PhD Student, Politehnica University of Timisoara, Faculty of Management in Production and Transportation, ramona-raluca.balau@student.upt.ro, 14 Remus str., 300191 Timisoara, Romania

Marius MIHUT, PhD Student, Politehnica University of Timisoara, Faculty of Management in Production and Transportation, marius.mihut@student.upt.ro, 14 Remus str., 300191 Timisoara, Romania

Anca DRAGHICI, Professor, Politehnica University of Timisoara, Faculty of Management in Production and Transportation, anca.draghici@upt.ro, 14 Remus str., 300191 Timisoara, Romania