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DIGITAL TECHNOLOGIES FOR QUALITY ASSURANCE IN CIRCULAR PRODUCTION SYSTEMS

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Abstract. The reason for this research stems from the urgent need to transform the agri-food industry into a sustainable system that can minimize food waste and meet increasingly stringent safety and quality requirements. The underlying hypothesis of this study is that integrating digital technologies and artificial intelligence can provide predictive and effective quality control in the circular economy. The research aims to analyze the impact of these technologies on food safety and waste reduction, and its objectives include identifying usable digital tools and evaluating their effectiveness in circular processes. The methodology employed consists of a conceptual and applied analysis of the role of technologies, including IoT, blockchain, computer vision, AI, and Big Data, in ensuring the quality of agri-food products. The results highlight a significant increase in traceability, operational efficiency and food risk prevention. The conclusion emphasizes the innovative nature of the use of digital technologies as transformation drivers in the agri-food industry. Their integration not only supports sustainability but also redefines quality assurance paradigms, setting the stage for self-optimizing food systems. The implications are far-reaching, with direct applications in the design of safe, transparent and zero-waste-orientated value chains.

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Keywords: circular economy, agri-food industry, digital technologies, artificial intelligence, quality, food safety, food waste, traceability.

Abstract. Justificarea acestei cercetări provine din nevoia urgentă de a transforma industria agroalimentară într-un sistem durabil care poate reduce la minimum risipa alimentară și poate îndeplini cerințe din ce în ce mai stricte de siguranță și calitate. Ipoteza care stă la baza acestui studiu este că integrarea tehnologiilor digitale și a inteligenței artificiale poate oferi un control predictiv și eficient al calității în economia circulară. Cercetarea își propune să analizeze impactul acestor tehnologii asupra siguranței alimentare și reducerii risipei, iar obiectivele sale includ identificarea instrumentelor digitale utilizabile și evaluarea eficacității acestora în procesele circulare. Metodologia utilizată constă într-o analiză conceptuală și aplicată a rolului tehnologiilor, inclusiv IoT, blockchain, computer vision, AI și Big Data, în asigurarea calității produselor agroalimentare. Rezultatele evidențiază o creștere semnificativă a trasabilității, a eficienței operaționale și a prevenirii riscurilor alimentare. Concluzia subliniază caracterul inovator al utilizării tehnologiilor digitale ca motoare de transformare în industria agroalimentară. Integrarea acestora nu numai că sprijină durabilitatea, ci și redefinește paradigmele de asigurare a calității, pregătind terenul pentru sisteme alimentare auto-optimizate. Implicațiile sunt de mare anvergură, cu aplicații directe în proiectarea unor lanțuri valorice sigure, transparente și orientate către zero deșeuri.

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Cuvinte-cheie: economie circulară, industria agro-alimentară, tehnologii digitale, inteligență artificială, calitate, siguranță alimentară, risipă alimentară, trasabilitate.

Introduction

The agri-food industry is facing increasing pressure to become more sustainable. Globally, one-third of the food produced for human consumption is lost or wasted, resulting in a significant economic, social, and environmental impact [1]. On the other hand, the demand for safe and quality food is constantly increasing, imposing rigorous monitoring and control standards along the entire supply chain. In this context, the circular economy provides a fundamental framework for redefining the way we produce, consume, and manage agri-food resources, shifting from a linear model („take-produce-use-throw") to a regenerative one [2].

However, the transition to a circular food system is not without challenges, especially in terms of ensuring quality and safety, given the complexity of material cycles and the possible variation of recycled or revalued raw materials. This is where digital technologies and Artificial Intelligence (AI) come into play, becoming essential enablers. They enable unprecedented visibility, intelligent automation, and process optimization, transforming the way quality is monitored, controlled, and improved at every stage of the circular food product lifecycle [3]. The essential role of innovation is highlighted in promoting a sustainable circular economy and strengthening food security, especially in the context of emerging economies dominated by small and medium-sized enterprises (SMEs). There is a pressing need for investments in research and development, as well as cooperation between business and academic institutions, to overcome financial barriers and stimulate the technology transfer necessary for sustainable progress [4]. In this article, we will explore in detail how these technologies are helping to build a safer, more efficient and less wasteful food future.

Fundamentals of the circular economy and quality assurance in the agri-food industry

The circular economy in the agri-food sector extends beyond simple recycling, incorporating a range of strategies designed to keep products, components, and materials in use for as long as possible. The main principles include reduction (minimizing waste at the source), reuse (extending the life of products and packaging), repair (repairing defects), remanufacturing (remaking products to new standards), and recycling (transforming waste into new resources) [5].

In the agri-food industry, these principles can be translated into:

- Reducing losses on the farm and in processing, namely optimizing harvests, transport and production processes to minimize waste from the outset.
- Reusing packaging, namely using return and refill systems for containers and containers.
- Valorization of by-products and organic waste, namely the transformation of production residues or unsold food into new ingredients, feed, energy or biogas. This also includes upcycling, which gives higher value to waste.

However, the adoption of the circular economy in the agri-food industry brings unique challenges related to quality assurance. Recycled raw materials or by-products can vary in quality, and the risk of contamination is a constant concern. For example, the quality of reclaimed water or reused packaging must be impeccable to guarantee food safety [6]. Without appropriate monitoring and control tools, consumer trust can be undermined, and health risks can increase. Ensuring full traceability across multiple cycles and managing complex data is also critical to navigating these challenges and complying with strict regulations in the field. Quality assurance is a proactive approach focused on preventing defects. The key principles of quality assurance are presented in the following figure 1.

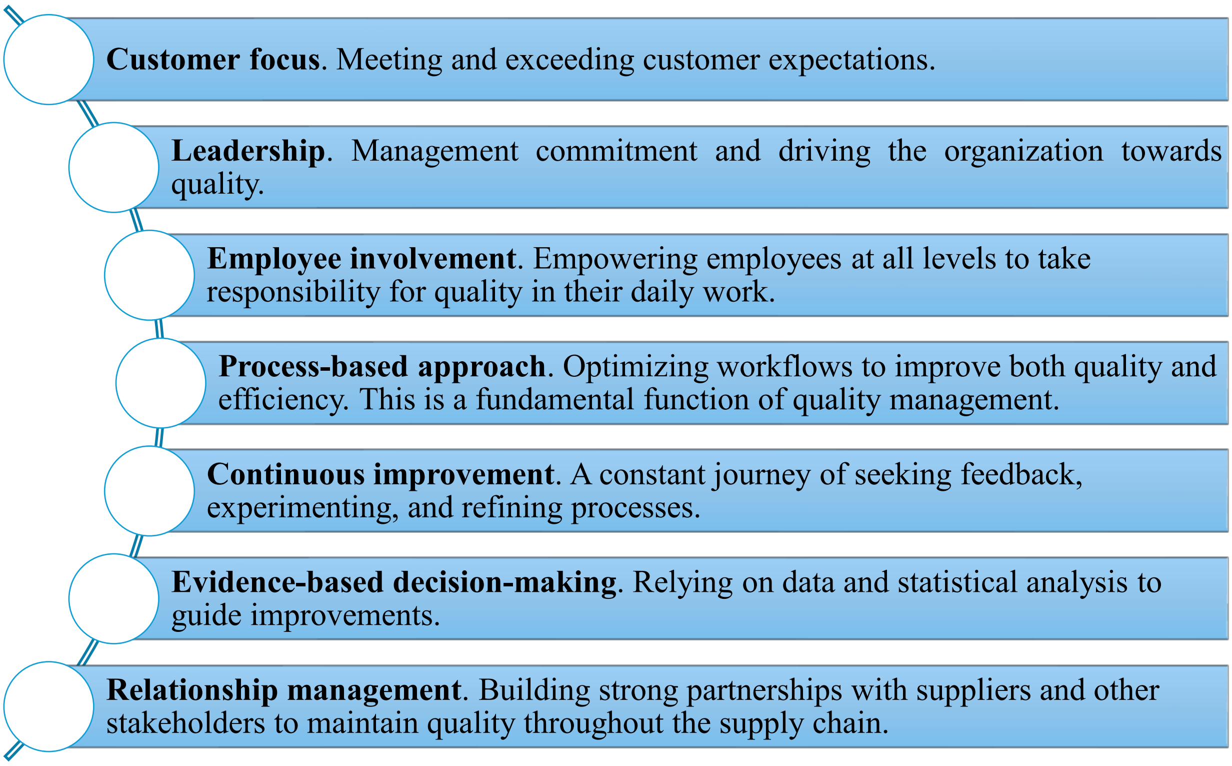

Figure 1. Key principles of quality assurance

Source: developed by the author based on [7].

Among the quality assurance activities, we can highlight the certification and assessment of suppliers, material testing, proper reception / storage / delivery, quality audits, process control, corrective actions and continuous monitoring. Quality improvement is achieved, in particular, by increasing the effectiveness and efficiency of processes. Quality 4.0 is a natural extension of Industry 4.0, explicitly focusing on quality management. It leverages digital tools and data-driven techniques for real-time collection, analysis and feedback mechanisms, enabling faster and better-informed quality control and assurance decisions. The integration of digital technologies fundamentally transforms quality assurance from a predominantly reactive or even proactive (prevention-focused) function into a predictive and self-optimizing one. Instead of identifying and correcting defects (quality control) or preventing them before they occur (quality assurance), digital technologies enable the prediction of potential problems before they manifest. This, in turn, enables dynamic, real-time adjustments to processes, significantly reducing the likelihood of defects and optimizing resource utilization. This shift is essential for the circular economy, where the variability of input materials makes traditional quality assurance more challenging. This evolution requires a change in the skill set required of quality professionals, transitioning from conventional inspection and auditing to data science, analytics, and systems optimization.

But let's not forget the personnel involved in quality assurance. As the transition to Industry 4.0 and later to Industry 5.0 progresses, the role of human resources in quality assurance becomes increasingly complex and essential. The integration of advanced digital technologies, such as data analytics, artificial intelligence and automation, requires a strategic realignment of employee skills with the new operational requirements of the circular economy. Thus, quality can no longer be guaranteed exclusively through technical tools but also through an adaptable, innovative workforce capable of collaborating effectively in digital environments. Therefore, skill gaps can be overcome through targeted upskilling and reskilling initiatives, contributing to the formation of a resilient and sustainability-oriented team. In the vision of Industry 5.0, the emphasis shifts towards a human-centric approach, where quality is the result of a symbiosis between technology and human creativity, which is an essential element for circularity and continuous innovation [8].

The role of digital technologies in ensuring food quality and safety

The integration of digital technologies offers robust solutions to overcome quality challenges in circular production systems in the agri-food industry. These tools enable precise monitoring, intelligent automation and unprecedented visibility over the entire value chain.

For example, the Internet of Things (IoT) is a network of physical devices, sensors, and software that enable the collection and exchange of data in real time. In the circular agri-food industry, IoT sensors can be integrated at every step of the process, from the smart farm to the point of sale. Among the devices used, we can highlight temperature and humidity sensors in warehouses and transport vehicles that monitor food storage conditions, preventing spoilage. Sensors can detect the level of ripeness of fruits and vegetables, optimizing the timing of harvest and distribution. On production lines, sensors can measure process parameters (pH, viscosity, composition), ensuring consistent product quality [9]. RFID tags and proximity sensors can also track the movement of reusable packaging, ensuring its timely sanitization and return for reuse.

Through continuous monitoring, IoT enables the rapid detection of deviations from optimal conditions, thereby preventing food spoilage and waste. This data can be used to optimize transportation routes, minimize post-harvest losses, and ensure that products reach consumers in fresh and safe conditions. In a circular context, IoT helps verify the hygiene of reusable packaging and the storage conditions for revalued raw materials, guaranteeing their safety.

Another tool could be Blockchain. Blockchain is a distributed and immutable ledger technology ideal for creating a complete and transparent audit trail of products. In the agri-food industry, where traceability is essential for consumer safety, Blockchain can revolutionize the way product data is recorded and accessed. Every stage of a food product's lifecycle, from the sourcing of raw materials (including recycled or upcycled materials) to processing, packaging, transport and distribution, can be recorded on a blockchain. This creates a „digital fingerprint" of each batch or even each individual product [10]. Consumers can scan a QR code to access detailed information about the product's origin, processing and quality. This tool provides end-to-end traceability, increasing transparency and trust. In the event of a food safety issue, the source of contamination can be identified quickly and accurately, allowing for more efficient product recalls and minimizing health risks. It also helps combat food fraud and verify the authenticity of products labelled as sustainable or „circular", strengthening the integrity of the supply chain [11].

Another helpful tool could be computer vision, which uses cameras and advanced algorithms to „see" and interpret images, enabling automated quality inspection on a large scale. Computer vision systems can automatically inspect fruits and vegetables for defects, blemishes, dents, or signs of deterioration, sorting them based on quality and freshness. They can also identify foreign bodies in processed food products and play a crucial role in the automated sorting of packaging for recycling, recognizing the type of material (plastic, glass, or metal) and the degree of contamination [12]. This technology offers consistent and rapid inspection, surpassing the capabilities of human inspection. It reduces errors and increases the efficiency of selection and sorting processes, ensuring that only the highest-quality products reach the market and that recyclable materials are sorted correctly to maintain the value of the circular economy. In a circular context, this tool contributes to reducing waste by redirecting products with minor defects to other value chains or energy recovery, thereby preventing them from becoming waste.

Currently, one of the modern tools that has seen rapid development in recent years is Artificial Intelligence (AI). Namely, Artificial Intelligence (AI), primarily through machine learning (Machine Learning), is the engine behind many digital technologies, allowing systems to learn from data, make predictions and make autonomous decisions.

Machine learning (ML) enables systems to identify complex patterns in large datasets and make predictions. ML algorithms can analyze historical and real-time data from IoT sensors (such as temperature, humidity, and composition) to provide information and sales data, predicting food shelf life, the risk of spoilage, or the occurrence of quality defects. Based on these predictions, companies can adjust distribution strategies or initiate promotions to sell products before they spoil. Similarly, ML can optimize production planning by predicting consumer demand, thus reducing overproduction and waste [13]. In a circular context, ML can assess the quality of by-products or recycled raw materials and recommend the best uses for them, maximizing value and minimizing waste.

By anticipating quality issues and optimizing production flows, ML directly contributes to reducing food waste. It ensures that products are fresh upon delivery and that resources are used efficiently, supporting food safety and sustainability goals.

Let's not forget about robots and automated systems that are transforming handling and processing processes in the agri-food industry, increasing efficiency and hygiene. Collaborative robots can delicately handle fragile food products, reducing damage and waste. They can perform precision sorting of fruits, vegetables or packaging, including those for recycling, with superior speed and accuracy. Automation is also crucial in the cleaning and sanitizing processes of equipment and reusable packaging, ensuring high standards of food safety [14].

The implementation of robotics minimizes human contact with food, significantly reducing the risk of microbial contamination. The precision and repeatability of robots ensure consistent product quality and increased efficiency in managing materials in circular loops.

However, any tool described above requires a vast amount of data. Namely, Big Data refers to the enormous volumes of data generated by digital technologies (such as IoT, sensors, and transactions), and digital platforms are the infrastructures that enable the collection, storage, processing, and analysis of this data. Data collected from all stages of the circular value chain (from production and distribution to consumption and waste management) is centralized and analyzed to identify trends, inefficiencies and opportunities for improvement. Digital platforms can facilitate connections between food producers and by-product valuers or between companies with surpluses and charities to redistribute food and reduce waste [15]. They also enable the monitoring of environmental and social performance throughout the entire life cycle, facilitating the assessment of compliance with circular principles.

Big Data analysis provides comprehensive visibility into the entire circular supply chain, enabling the rapid identification of sources of waste and critical quality control points [16]. Digital platforms optimize material flows, ensuring that resources are utilized to their maximum potential, thereby increasing efficiency and, implicitly, contributing to food safety through proactive risk management.

Implementing digital technologies for quality assurance in circular production systems within the agri-food industry offers significant benefits but also presents inherent challenges.

Among the significant benefits that digital technologies can bring, we can list:

- Increase food safety. This can be ensured through continuous monitoring with IoT, precise traceability with blockchain and automated inspection with computer vision, drastically reducing the risks of contamination and alteration. Consumers have access to detailed and verified information about the products they purchase.
- Substantial reduction in food waste, which is ensured by digital technologies that optimize each stage, from demand prediction with AI, which avoids overproduction, to efficient waste sorting and by-product recovery. This leads to a more innovative use of resources and minimizing losses throughout the circular supply chain [17].
- Operational efficiency and cost reduction can be achieved through process automation, inventory and logistics optimization, as well as preventing product losses, which can lead to significant cost savings and increased productivity.
- Improving traceability and compliance. The ability to track each product from source to consumer and demonstrate compliance with strict food industry regulations becomes simpler and more reliable.
- Developing new business models. Ultimately, however, digital technologies facilitate the emergence of new services and products based on circular principles, such as food surplus-sharing platforms or innovative waste management services.

Among the challenges, risks that digital technologies can bring, we can highlight the following:

- High initial costs. Implementing complex digital infrastructures (sensors, software, robots) requires substantial investments, which can be a barrier for small and medium-sized enterprises and, especially, for those starting their businesses.
- Interoperability of systems. A significant technical challenge would be ensuring that different technologies and platforms can communicate and share data efficiently.
- Data security and privacy. The collection and storage of large volumes of sensitive data require robust cybersecurity measures to prevent attacks and data breaches.
- Lack of digital skills. There is an acute need for a skilled workforce capable of operating and managing these advanced technologies.
- Evolving regulations and the need for standardization. The legal and regulatory framework must keep pace with technological innovations, particularly in terms of ensuring the safety and traceability of circular products. The development of common standards is essential for large-scale adoption [18].

Conclusion

The integration of digital technologies and Artificial Intelligence is a fundamental driving force in transforming the agri-food industry towards a circular production model. Through the ability to monitor, analyze, predict and automate processes, these innovations contribute decisively to increasing food safety and drastically reducing food waste. From real-time freshness monitoring with IoT to tamper-proof traceability ensured by blockchain to intelligent inspection with computer vision and flow optimization with machine learning, each technology plays a vital role in building a more robust and responsible food value chain. Prospects point to an even deeper integration of these technologies, with the potential to create self-optimizing food systems where data is maximized to prevent losses and ensure quality. Despite the challenges, investing in digitalization and AI is not just an option but a strategic necessity for agri-food companies that aim to thrive in a future dominated by the principles of the circular economy. Collaboration among industry, academia, and government authorities will be crucial to overcoming obstacles and maximizing the enormous potential of digital technologies in building a safer, more efficient, and truly sustainable global food system.

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