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The Impact of Smart Packaging on the Digitalization of Supply Chains

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ABSTRACT

The food supply chain (FSC) plays an extremely important role in society and the global economy, while at the same time facing numerous challenges, among which packaging occupies a key position. Traditional forms of packaging often contribute to increased losses, higher costs, and reduced overall food supply chain efficiency. This paper analyzes the application of smart packaging, namely active packaging, intelligent packaging, and QR code-based packaging, as alternative solutions that can contribute to extending product shelf life, preserving quality, and improving product traceability throughout food supply chains. These alternatives are compared based on a defined set of nine criteria using a hybrid model that integrates the fuzzy best-worst method and the fuzzy combined compromise solution method. Special emphasis is placed on the importance of smart packaging in the digital transformation of the food supply chain, particularly through its connection with modern technologies. The obtained results indicate that the analyzed solutions contribute to increasing the transparency, efficiency, and long-term sustainability of food supply chains. The paper shows that future development in this field is directed toward integrating digital technologies with environmentally friendly materials to reduce waste, preserve freshness, and enhance the resilience of food supply chains.

1. Introduction

The food supply chain (FSC) is one of the most complex and sensitive supply chains, as it includes processes ranging from production and processing to storage, transportation, and the distribution of products to end consumers [1,2]. It involves products with a limited shelf life, which require specific storage and transportation conditions, as well as a high level of quality and safety control [3]. It is estimated that food production will increase by approximately 70% by 2050 due to market globalization and the introduction of a large number of intermediaries [4,5]. This increases competition, while contemporary challenges include waste reduction, ensuring traceability, cost control, and compliance with environmental requirements [6]. Therefore, the FSC is particularly exposed to risks, ranging from product spoilage and contamination to waste generation and the loss of economic value. The key challenges faced by FSCs include preserving product quality and

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freshness, reducing food waste, complying with environmental requirements, and adapting to growing consumer expectations for transparency and traceability [7].

Food safety is a key global challenge for numerous reasons, including environmental and political factors, as well as deficiencies in processing, packaging, transportation, distribution, and storage. In addition, approximately 15% of global food production is discarded before reaching retailers due to packaging-related issues [3,8]. Traditional approaches are often insufficient to address these challenges, particularly in the context of globalized markets and increasing competition. In this regard, digitalization and the application of modern technologies are becoming essential tools for improving the efficiency and enhancing the resilience of FSCs [9,10]. Digitalization and smart packaging enable real-time monitoring of food quality, extend product shelf life, and reduce losses, thereby improving the efficiency and sustainability of FSC [6,7]. Among the innovative solutions that directly contribute to overcoming key FSC challenges, smart packaging stands out as a concept that goes beyond the traditional role of product protection and becomes an active element of the digital SC. Its application enables the monitoring of storage and transportation conditions in real time, extends product shelf life, and reduces the risk of losses, thereby contributing to both the economic and environmental objectives of modern business [2,7].

The paper is structured as follows. Following the introduction, the second section specifies the key challenges in the FSC and the importance of digitalization in overcoming them. Then, in the third section, the key problems that cause losses in the FSC are analyzed in detail through a concrete example of a logistics company involved in the production, processing, and packaging of fresh meat and meat products. Based on this, the fourth section defines alternative smart packaging solutions, as well as the criteria for their ranking. To compare and rank the alternative solutions, a hybrid multi-criteria decision-making (MCDM) model is applied. The conclusion presents the key contributions and a summary of the entire paper, as well as directions for future research.

2. Problem Description

FSC connects producers, processors, distributors, retailers, and consumers, while its complexity stems from the very nature of food products, which are characterized as perishable goods and require high standards of safety and quality. Packaging plays a particularly important role in the FSC, as it not only preserves freshness and extends product shelf life but also affects the efficiency of storage and transportation processes, as well as consumer perception [5,11]. Inadequate packaging generates losses and waste. Therefore, modern technologies and smart packaging are key to improving sustainability, control, monitoring, and optimization within the FSC. Considering the goal of reducing food waste by approximately 50% by 2030 [3,6], food packaging represents one of the essential activities within the FSC. These activities are considered to provide the main protective barrier for food products against external influences. However, numerous studies indicate that up to 30% of food products spoil during storage and transportation due to packaging-related problems [10,11]. Therefore, the application of modern packaging solutions can play a decisive role in preventing food waste, which is important from both economic and environmental perspectives [1,4]. Conventional food packaging is most often intended for single use and becomes waste after use, which is why materials such as paper, plastic, glass, steel, and aluminum are commonly used. Paper and cardboard packaging have relatively high recycling rates, whereas plastic remains a major environmental problem due to its unsustainability and recycling rate of less than 20% [2,10]. In addition to protecting food, the packaging method has a significant impact on intralogistics processes within a company. Packaging is often performed manually, which creates problems not only in terms of quality but also in terms of increased costs and longer process durations [4,6].

The analysis of a logistics company engaged in the production, processing, and packaging of fresh meat and meat products revealed that the company faces significant problems related to the efficiency and costs of product packaging. The current packaging process, based on manual wrapping with PVC film and heat sealing, shows several shortcomings, including long processing time, susceptibility to errors, insufficient product protection, and a high risk of food contamination. Handling often results in packaging damage, while the human factor in the control stage further increases the possibility of omissions. These shortcomings are reflected in increased costs of repackaging and equipment maintenance, the need for continuous employee training, prolonged packaging time due to manual control, degradation of product quality caused by film damage, and negative consumer perception of the brand in cases where damaged products are displayed.

The packaging problem is not limited to the company itself but has consequences for the entire FSC. Insufficient protection of meat products leads to spoilage, which requires faster delivery and shortens the period during which products remain suitable for sale. Damaged packaging often results in the complete loss of products, since meat cannot be recycled or reused, thereby generating large amounts of waste and environmental problems. Inadequate packaging affects the company’s internal processes and destabilizes the entire FSC, leading to increased costs, greater resource requirements, higher levels of waste, and reduced system flexibility in adapting to market changes [10,11].

3. Alternative Solutions for the Digitalization of Food Supply Chains

The introduction of smart packaging emerges as a potential solution for overcoming the identified challenges. The application of different forms of intelligent, active, or interactive packaging with QR codes can significantly contribute to waste reduction, increased safety, and improved efficiency of the entire SC. In addition, the integration of modern technologies, such as artificial intelligence (AI) for predictive analytics, Internet of Things (IoT) sensors for real-time monitoring of product conditions, blockchain for transparent and secure FSC tracking, and digital twins for the simulation and optimization of operations, further enables the enhancement of SC resilience and agility [1,11].

3.1 First Alternative: Intelligent Packaging

Intelligent packaging refers to packaging with embedded sensors and indicators, such as freshness and temperature indicators, which enable the detection of changes inside and outside the package and provide information on product quality throughout the entire FSC. Some solutions also monitor and actively regulate heating and cooling conditions; e.g., through water evaporation in meat products and use ethylene absorbers to slow ripening and extend the shelf life of fresh food [12]. The advantages of intelligent packaging include faster and automated sorting, early detection of quality-related risks, simpler control through sensor signals, real-time monitoring that facilitates shelf-life management and reduces waste, better control of transportation conditions, increased safety through the detection of tampering attempts, and a reduced share of manual work with fewer errors. The disadvantages are related to high initial costs, demanding integration with existing systems, the need for employee training, and increased operating costs [13].

3.2 Second Alternative: Active Packaging

Active packaging refers to packaging that interacts with the product or the atmosphere inside the package to preserve quality and extend shelf life. Active components, either natural or synthetic, are incorporated into the packaging, such as oxygen absorbers, carbon dioxide absorbers, moisture regulators, antimicrobial agents, and antioxidant agents. The controlled absorption or release of these substances by active packaging slows undesirable changes and helps maintain product freshness [14]. The advantages of active packaging include extending the freshness and shelf life of meat products, reducing the frequency of stock replenishment and food waste, providing better protection during transportation and handling with fewer damages, and reducing the need for repackaging and additional handling activities. This can lower material and labor costs, particularly in automated systems. The disadvantages include higher costs and greater complexity, the need for new equipment and employee training, sensitive components that require careful handling, and possible consumer reluctance toward the use of chemical agents [12,13].

3.3 Third Alternative: Packaging with QR Codes

QR code-based packaging belongs to the category of smart packaging that increases the availability of information throughout the entire FSC. QR codes are printed and attached to the packaging, while the data becomes accessible by scanning them with mobile devices. This ensures greater transparency and traceability of shipments. Some variants use chemical components that react to volatile substances associated with changes in food quality. In such cases, a change in the color of the QR code indicates quality deterioration [14]. The advantages of this solution include immediate visibility of product status after scanning. Inventory is automatically updated, while expiration dates are monitored upon receipt. This reduces the risk of product expiration and waste. Order picking becomes faster because manual data entry is eliminated. QR codes can be connected to the entire system and line equipment for automatic routing. Printing costs are low, while the benefits of automated scanning are significant. The disadvantages are reflected in high investment requirements. Employee training and the establishment of procedures for automatic scanning are necessary. In addition, QR codes must be protected from damage to remain readable [15].

3.4 Criteria Evaluations

Criteria represent the key elements for comparing and ranking alternative solutions (i.e., packaging solutions) [16]. In this paper, nine criteria were used, covering technological aspects as well as all dimensions of sustainability [17,18]:

i. *Real-time monitoring* (C_1) – The ability of packaging to provide accurate information on the condition of the product at any given moment.
ii. *Integration with the existing system* (C_2) – The extent to which a new type of packaging can be integrated with the company's existing equipment and processes.
iii. *Packaging resistance* (C_3) – Resistance to mechanical damage, temperature changes, and humidity during transportation and storage.
iv. *Investment costs* (C_4) – The costs of acquiring packaging materials and additional equipment.
v. *Operating costs* (C_5) – These include all costs related to daily packaging processes, such as energy, labor, and packaging materials.
vi. *Maintenance costs* (C_6) – Maintenance costs include all regular and extraordinary costs related to the maintenance and repair of packaging equipment.
vii. *Food safety* (C_7) – The level of consumer protection against contaminated meat, which is crucial for consumer health and safety.
viii. *Environmental impact* (C_8)– The contribution of packaging to reducing negative environmental impacts through recycling and waste reduction.
ix. *Transparency* (C_9) – The extent to which packaging can provide consumers with important information about the origin, freshness, and safety of the product.

4. Hybrid Multi-Criteria Decision-Making Model

In this paper, a hybrid MCDM model combining the fuzzy best-worst method (BWM) [19] and the fuzzy combined compromise solution (CoCoSo) method [20] was applied. Fuzzy BWM was used to determine the criteria weights because it reduces the inconsistency of expert judgments with a small number of pairwise comparisons and enables more stable weighting. Fuzzy CoCoSo was applied to rank the alternatives, as it integrates multiple aggregation schemes and provides a compromise solution suitable for balancing conflicting objectives. Both methods were developed in a fuzzy environment because the evaluation of intelligent packaging necessarily involves uncertainty and imprecision in empirical assessments, as well as the subjectivity of expert judgments.

The first step of the model involves determining the criteria weights using fuzzy BWM. First, the most important criterion was identified, after which the remaining criteria were compared against the most important one. By applying the fuzzy BWM method, the criteria weights were calculated (Table 1).

Table 1
Criteria weights

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Type	max	max	max	min	min	min	max	max	max
Weights	0.302	0.181	0.121	0.091	0.091	0.072	0.060	0.052	0.030

After determining the criteria weights, an expert evaluation of the alternatives with respect to the criteria was conducted. The sample consisted of supply chain experts with at least five years of experience. Each expert independently evaluated the alternatives using a standardized scale from one to nine. The obtained fuzzy ratings were aggregated to form an overall assessment for each alternative with respect to each criterion. The aggregated ratings of the alternatives according to the criteria are presented in Table 2.

Table 2
Ratings of the alternatives by the criteria

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	9	5	4	3	5	5	9	5	7
A_2	5	5	5	5	5	5	7	5	3
A_3	5	7	6	9	7	7	3	7	9

After the application of fuzzy CoCoSo, the following ranking of the alternatives was obtained (Table 3).

Table 3
Ranking of the alternatives

Alternatives	K_i	Rank
A_1	3.949	1
A_2	2.331	2
A_3	1.396	3

A_1 ranks first because it achieves balanced results across most criteria, particularly in terms of food safety and monitoring functionality. In addition, it is relatively favorable in terms of moderate investment and operating costs, which enables it to achieve the highest overall value compared with the other alternatives. A_2 demonstrates very good performance in real-time monitoring and food safety. However, its higher initial costs and lower packaging resistance reduce its overall performance, placing it behind A_1. A_3 offers the most favorable investment costs, good integration, and a high level of transparency for consumers. However, weaker food safety performance and a moderate monitoring capacity reduce the overall performance of A_3, which places it last in the ranking.

5. Conclusion

FSC represents a complex system that has a significant impact on the everyday life of society and the economy at both regional and global levels. Traditional packaging often limits the efficiency of logistics processes, increases losses, and makes product monitoring more difficult. In contrast, smart packaging plays a key role not only in overcoming these problems but also in the digitalization of the FSC. Active packaging, intelligent packaging, and QR code-based packaging enable real-time monitoring of product conditions, improved quality control, optimization of storage and transportation processes, and increased transparency throughout the FSC. The integration of these technologies with digital and modern solutions, such as IoT sensors, AI, and blockchain, further strengthens the flexibility and resilience of the system, reduces losses, and contributes to sustainability.

The selection of a smart packaging type is of great importance because it directly affects food safety, shelf-life extension, and FSC efficiency. In addition, the selection of an appropriate packaging technology contributes to cost reduction, food waste reduction, and consumer satisfaction, while simultaneously supporting sustainability objectives. Furthermore, linking packaging solutions with modern digital technologies enables better traceability and transparency, thereby strengthening customer satisfaction and competitiveness within the FSC.

Future research may focus on the further development and improvement of smart and environmentally friendly packaging, as well as on evaluating its impact on the digitalization and efficiency of the FSC. In addition, the study could be expanded by considering a broader set of defined criteria and alternatives, which would provide a more comprehensive understanding of the problem being addressed. Future extensions may also focus on analyzing the application of these packaging solutions to other specific products, such as fresh fruits and vegetables, milk and dairy products, pharmaceutical products, and similar product categories.

Conflict of Interest
The authors declare no conflict of interest.

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