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Mapping the potential of smart packaging for sustainable transition in the fashion industry.

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This paper investigates the role of smart packaging technologies as enablers of sustainability and circularity within the fashion supply chain. The study aims to map the current state of digital packaging solutions across industries to identify their potential applications and benefits in fashion. The fashion industry represents a heavy burden in terms of environmental impact produced by the intensive consumption of raw materials and the substantial volume of waste generated across product life cycles. Moreover, the globalised and fragmented nature of the fashion supply chain enhances complexity and hinders transparency, making circular transformation particularly difficult to manage. The paper is organised as follows: first, a literature review and a case study analysis outline the development and use of smart packaging technologies in sectors such as food, pharmaceuticals, and consumer goods. Next, a policy analysis highlights the evolving European regulatory framework, emphasising how digital integration in packaging aligns with broader sustainability goals like the European Green Deal and Circular Economy Action Plan. Through this multi-dimensional approach, the study identifies key opportunities for smart packaging to enhance transparency, product traceability, consumer engagement, and lifecycle management in fashion. The paper concludes by discussing future research directions and the transformative potential of smart packaging in supporting a sustainable transition within fashion supply chains. This work contributes to the dialogue on digital innovation and circular economy strategies, offering insights for designers, manufacturers, and policymakers aiming to leverage packaging as a catalyst for sustainability in fashion.

Keywords: Smart packaging; digital technologies; fashion supply chain; sustainable transition

1 Introduction

The fashion industry is among the most environmentally impactful sectors globally (Boström & Micheletti, 2016) due to its intensive consumption of raw materials and the substantial volume of waste generated across product life cycles. This industry contributes approximately 2% to 10% of the overall environmental footprint in Europe. However, fewer than half of discarded garments are collected for reuse or recycling, and a mere 1% is successfully recycled into new textiles. This significant gap primarily depends on the underdevelopment of recycling technologies (Sajn, 2019). Each year, approximately 5.8 million tonnes of textiles end up in landfills

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across Europe, equating to about 15 kg per person (European Environment Agency, 2022). These scenarios exemplify a predominantly linear model of production and consumption, depicting a value chain that remains far from becoming circular.
Several interrelated factors contribute to this unsustainability. The widespread fast fashion—characterised by low-quality products, reduced garment lifespans, and rapid consumption cycles—has intensified environmental impacts and resource depletion (Vezzoli et al., 2020). Moreover, the globalised and fragmented nature of the fashion supply chain (Boström & Micheletti, 2016) hinders transparency and make circular transformation particularly difficult to manage.
The growing dominance of e-commerce has further exacerbated these challenges. Over the past two decades, global e-commerce sales have grown by an average of 31% per year, reaching approximately six trillion USD in 2024 (Statista, 2025). Fashion is one of the most significant segments in this market, with online sales representing 21% of total fashion purchases in 2023 alone (Statista, 2024). This shift has dramatically increased the speed and volume of product circulation, introducing new sustainability concerns linked to logistics and packaging. Transportation-related emissions and packaging waste now represent two of the most pressing environmental issues in the fashion e-commerce model (Barbero & Pereno, 2020).

Within this evolving context, packaging is emerging as a critical intervention point. Once a passive container, packaging has now evolved into a complex communication tool (Ciravegna, 2010). The rise of new digital technologies has paved the way for new possibilities, enabling the tracking of supply chain data, ensuring product integrity, safety and authenticity, and recording key information related to social and environmental impact across the product lifecycle. This shift makes packaging a strategic mediator within the supply chain: a functional element and a broadcasting tool capable of engaging end users, facilitating transparency, and connecting different stakeholders along the value chain. Thus, packaging offers an opportunity to support circular transitions by informing, educating, and empowering businesses and consumers.
At the policy level, the European Union has introduced ambitious frameworks to reshape the textile sector through sustainability and circularity principles. Initiatives such as the European Green Deal, the Circular Economy Action Plan, and the EU Strategy for Sustainable and Circular Textiles promote durability, reparability, and recyclability while discouraging overproduction and short-lived fashion. Among the most innovative instruments is the Digital Product Passport (DPP), designed to embed standardised product information throughout the supply chain to improve traceability, resource efficiency, and regulatory compliance (Bjørn & Sivert, 2023). These regulatory signals highlight the growing importance of leveraging packaging as a vector of circularity and transparency. In alignment with these developments, the research project FuturE-Pack - Digital Advanced Design for the Enhancement of Packaging as a "Broadcaster" in the Made in Italy Supply Chain - aims to rethink the role of packaging in the context of the fashion industry. Developed as part of the MICS Extended Partnership and funded by the European Union's NextGenerationEU program, the project brings together research teams from the University of Bologna, the University of Florence, and the Politecnico di Torino. It explores how digitally enhanced packaging can move beyond protective and logistical functions to act as a communication infrastructure supporting sustainable transitions.
While most smart packaging innovations have emerged in sectors such as food, pharmaceuticals, and consumer goods, this study specifically investigates their transferability to the fashion context. The peculiar combination of aesthetic, material, and logistical dimensions that characterises the fashion industry requires tailored adaptation strategies. Accordingly, the research examines how smart packaging technologies can be applied across different stages of the fashion supply chain to enhance transparency, traceability, and consumer engagement, identifying sector-specific opportunities and constraints that can support a transition toward circularity.

This article presents the preliminary outcomes of the project, focusing on the potential of digital technologies to enhance packaging as a vector of transparency and circularity in the fashion supply chain. The research outlines a taxonomy of packaging typologies through a review of existing literature and a selection of case studies. It examines the state of the art of digital technologies applied to packaging. The study identifies recurring trends, technological enablers, and strategic opportunities that can support a systemic transition toward circularity—highlighting the potential role of packaging within the fashion industry.

2 Smart Packaging

Once regarded as a simple means of containment, packaging has progressively transformed into a key element of product design, assuming essential functions of protection and preservation (Lydekaityte & Tambo, 2020). The acceleration of digital innovation is transforming the packaging role, which is increasingly evolving as a strategic tool in enabling the transition to a circular economy. It can encompass functions such as assessing life cycles, extending product durability, and supporting more sustainable supply chain practices. Thus, the notion of "packaging" in its traditional form appears insufficient, giving way to the broader and more advanced concept of "smart packaging." Smart packaging encompasses a set of solutions in which advanced technologies can enhance conventional functions or introduce entirely new capabilities. As Brockgreitens and Abbas (2016) described, these technologies aim to add value beyond basic functionality. According to Nandanwade Priyanka and Nathe Parag (2013), smart packaging can also react to changes in the product or its surrounding environment, thereby improving preservation and usability and facilitating communication along the supply chain, to the end consumer. These technologies may include a range of mechanisms, from chemical and mechanical systems to electronic components and digitally connected infrastructures.

Based on their primary function, the technology used, and the interaction between the product and the user, packaging solutions can be divided into three main categories (Figure 2): active, intelligent, and interactive packaging (Lydekaityte & Tambo, 2020; De Kruijf et al., 2002; Ozcan, 2020).

1. Active Packaging: Designed to modify the internal conditions of the packaging environment, this type of packaging aims to prolong shelf life or maintain product quality by releasing or absorbing specific substances. Mechanisms can include oxygen scavengers, antimicrobial agents, or humidity regulators.
2. Intelligent Packaging: This category integrates technologies that monitor, detect, and transmit information about the state of the product. Unlike active solutions, it does not interact with the product directly but provides relevant data to support logistics, safety, and quality control. Examples include freshness indicators, time-temperature indicators, sensors, RFID, QR codes, NFC tags, and augmented reality elements.
3. Interactive Packaging: These solutions aim to actively involve users by offering an enhanced experience through technological engagement. Interactive packaging enables real-time digital interaction through printed electronics, augmented reality, IoT systems, and standardized communication protocols. As Nilsson et al. (2012) highlighted, these systems facilitate access to web-based services, opening new possibilities in product communication and personalization.

3 Materials and Methods

The present study adopts a mixed-methods approach, combining an in-depth literature review, a structured case study analysis, and a targeted policy review. This approach was selected to comprehensively explore the role of digital technologies in advancing sustainable packaging solutions within the fashion supply chain. The methodology is divided into three core components.

3.1 Literature Review

The objective of the literature review was to establish a theoretical foundation for the investigation of smart packaging technologies and their relevance to logistics, packaging design and product delivery. A comprehensive review of academic journals, industry reports and regulatory documents was conducted to understand the existing and emerging digital solutions that are applicable to packaging.

3.2 Case Study Analysis

We adopted a qualitative case study approach to identify and examine 88 real-world applications of advanced digital packaging systems. The selected dataset comprises innovative solutions that integrate digital technologies into packaging. Each case was documented using a dedicated data collection tool, specifically designed to facilitate the structured gathering and systematisation of relevant information. Figure 1 illustrates the layout used for recording the data. For every case study, a standardised set of information was collected, including product name, company, country of origin, year of implementation, product category, type of digital solution (active or intelligent), and packaging characteristics.

Regarding the classification of packaging levels, reference was made to the Directive 94/62/EC of the European Parliament and of the Council of 20 December 1994 on packaging and packaging waste, which defines three levels of packaging: primary, secondary, and tertiary.

- Primary packaging is the first layer of packaging in direct contact with the product. It is intended as a sales unit for the end consumer and typically accompanies the product from the point of sale to the final user's home. This level of packaging often includes essential consumer information, such as expiry dates, and ensures product protection.
- Secondary packaging surrounds the primary packaging, grouping several sales units for easier handling and display at the point of sale. It facilitates distribution from warehouses to retailers and can generally be removed without affecting the integrity of the product or its primary packaging.
- Tertiary packaging (or transit packaging) is used for bulk handling and transportation, encompassing multiple primary or secondary units. It ensures product safety during long-distance logistics and is primarily used to move goods from production facilities to storage or distribution centers.

As for the classification of digital packaging solutions, the analysis distinguishes between intelligent and active systems (see Figure 2), recognizing that interactive packaging represents a subcategory of intelligent systems.

All information was collected through a structured Excel spreadsheet to ensure consistency across the documentation process. This approach enabled the organization of a diverse and heterogeneous dataset and the emergence of preliminary findings. Upon completing and reviewing all case entries, we conducted a comprehensive analysis, which allowed us to identify key trends and patterns. These findings contributed to formulating critical insights into how digital packaging is evolving to support a sustainable transition.

Case study #1	
Name	AGELESS™
Company	Mitsubishi Gas Chemical Co. Ltd
Country	Japan
Year	1997
Product category	Food
Type of Solution - Intelligent system	-
Type of Solution - Active system	Oxygen Scavengers
Packaging Level	Primary Packaging
Solution aim	Prolong the shelf-life of the product
Description	The AGELESS™, developed since 1997, is a bag containing iron powder that, reacting with oxygen, allows to remove oxygen by oxidizing iron powder, thus preventing food products from oxidizing in advance. It is also used to maintain the efficacy of medicine, protect metal and electronic parts, and even help preserve cultural artifacts such as books, textiles, and works of art.
Reference Link	https://www.mgctrading.co.jp/en/products/ageless.html

Figure 1. Example of case study layout.

This method aims to standardise information collection and bring out the first results in a structured and heterogeneous collection, thus comparing the results. For this reason, once all the case study forms were completed and collected, it was possible, thanks to an overall schematization of the volume of said cases, to propose final considerations aimed at identifying actual trends in the application of digital technologies to packaging.

3.3 Policy Analysis

The third phase of the research incorporated a policy analysis, the purpose of which was to contextualise the technological and practical insights within the broader regulatory landscape identifying major restrictions, potentials, and obstacles that may affect the application of digital technologies to packaging. We conducted the analysis at the European and national level, collecting information retrieved from government online public archives.

Table 1 presents a synthesis of the identified regulations, organised according to several criteria: institutional level (e.g., European, national), title, brief description, year of promulgation, web source, previous or updated version (if available), and—specifically for national regulations—the related EU reference, where applicable.

Level	Name	Description	Year	Link	Previous/ Updated version	EU referment
EU	**Ecodesign Directive 2009/125/EC**	It establishes a framework for the setting of ecodesign requirements for energy-related products	2009	Link		
EU	**WEEE Directive (2002/96/EC and 2012/19/EU)**	It imposes extended producer responsibility for the management of waste generated by their products at the end of their life cycle.	2002	Link		
EU	**REACH Regulation (1907/2006/EC)**	REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) is a regulation on the registration, evaluation, authorisation, and restriction of chemicals to ensure their safe use.	2006	Link		
EU	**CLP Regulation (1272/2008/EC)**	The CLP (Classification, Labelling, and Packaging) Regulation concerns the classification, labeling, and packaging of chemicals to ensure safety.	2008	Link		
EU	**Directive 94/62/EC**	Defines EU provisions on the management of packaging and packaging waste. It aims to harmonise national measures concerning the management of packaging and packaging waste;	1994	Link	Previous version of EU's Packaging and Packaging Waste Directive	
		improve the quality of the environment by preventing and reducing the impact of packaging and packaging waste on the environment.				
EU	**EU's Packaging and Packaging Waste Directive**	Latest amendment to Directive 94/62/EC and contains updated measures to prevent the generation of packaging waste, and	2018	Link	Updated version of Directive 94/62/EC	
EU	**2018/852**	promote reuse, recycling and other forms of recovery of packaging waste, rather than its final disposal, in order to contribute to the transition to a circular economy.				

EU	**Packaging and Packaging Waste Regulation (PPWR)**	Sets rules to minimise packaging waste and improve recyclability and reuse.	2022	Link	Updated version of Directive 94/62/EC	–
EU	**REGULATION (EU) 2023/826**	Defines ecodesign requirements for off mode, standby mode, and networked standby energy consumption of electrical and electronic household and office equipment	2023	Link	Updated version of Directive 2009/125/EC	
EU	**Procedure 2022/0095/COD**	Ongoing - Establishes a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC	2023	Link	Updated version of Directive 2009/125/EC	
EU	**European Green Deal**	Strategic roadmap to make the EU climate-neutral by 2050; includes actions for sustainable industry and circular economy.	2019	Link	–	–
EU	**Circular Economy Action Plan**	Pillar of the Green Deal; promotes product lifecycle extension, waste prevention, and packaging sustainability.	2020	Link	Updated version of 2015 plan	–
EU	**Ecodesign for Sustainable Products Regulation (ESPR)**	Framework for setting ecodesign requirements for sustainable products, including digital elements like product passports.	2022	Link		–
EU	**Sustainable Product Initiative**	Part of the ESPR; aims to make sustainable products the norm, especially through durability, repairability, and recyclability.	2022	Link	Introduced within ESPR	–
Italian	**Legislative Decree 49/2014**	This decree transposed the WEEE Directive and regulates the management of waste from electrical and electronic equipment in Italy.	2014	Link		
Italian	**Legislative Decree 152/2006**	This decree, known as the "Environmental Code," establishes general environmental rules in Italy and addresses various aspects of environmental management, including extended producer responsibility.	2006	Link		
Italian	**Law 221/2015**	This law promotes energy efficiency, the use of renewable energy sources, and product ecodesign.	2015	Link		
Italian	**UNI EN 13427: 2005 Imballaggi— Requisiti per l'utilizzo di norme europee nel campo degli imballaggi e dei**	The 'umbrella' technical standard UNI EN 13427 explains how many and which essential requirements apply: Manufacture and composition (source reduction, limited presence of heavy metals and hazardous substances or preparations), Reuse and Recovery (of material, energy, organic).	2005	Link	-	EU's Packaging and Packaging Waste Directive

	rifiuti di imballaggio	It also explains how to proceed: all packaging must comply with the prevention requirement, while only those designed and produced to be reused must comply with the reuse requirement. All packaging must comply with at least one of the three forms of recoverability				2018/852
Italian	**UNI EN 13428: 2005 Imballaggi— Requisiti specifici per la fabbricazione e la composizione**	It explains the manufacturing and composition requirement, which consists of three basic elements: prevention by source reduction, maximum presence of heavy metals, and maximum presence of hazardous substances or preparations.	2005	Link	-	

Table 1. Policy identified at European and national level

4 Results & Discussion

The result of the literature review and the in-depth study and systematisation of case studies led to the definition of a taxonomy of digital technologies applied to packaging design (see Figure 2), with a series of solutions that can meet the different needs and requirements of products, supply chain actors, and end users. The taxonomy is structured into six primary categories, divided by typology of packaging, i.e., active, intelligent and interactive (as a subcategory of the previous one, each of which is further organised into subcategories, as detailed below.
For the active packaging:

- Absorbers: oxygen scavengers, carbon dioxide scavengers, moisture scavengers, odour scavengers, ethylene scavengers.
- Emitters: oxygen emitters, carbon dioxide emitters, flavour emitters.
- Preservative releasers: Antimicrobial agents, Antioxidant agents.
  For the intelligent packaging:
- Data Carrier: Barcodes, QR Codes, RFID (Radio-Frequency Identification) Tags, NFC (Near Field Communication) Tags, Digital watermarks, AR (Augmented Reality)/ WebAR Codes, VR (Virtual Reality) Codes, those technologies, when integrated with internet can allow the interaction with the user thus making the packaging also interactive.
- Indicators: Freshness indicators, Time-temperature indicators, integrity, Gas indicators
- Sensors: Biosensors, Gas sensors, Temperature sensors, Movement sensors, Humidity sensors, chemical sensors

Figure 2. Taxonomy of digital technologies applied to packaging. Source: author's elaboration.

We developed this taxonomy to support the structured collection, classification, and subsequent analysis of case studies. It served as a framework for identifying and organising relevant examples, specifically those focusing on digital solutions for product labelling, tracking, and tracing.
The 88 international case studies collection provides a comprehensive overview of the application of digital technologies to packaging solutions across different sectors and packaging levels. Each case was analysed using a standardised template (see Paragraph 3), capturing key variables—such as type of packaging (active or intelligent), packaging level (primary, secondary, tertiary), product category, and enabling technologies. This section highlights recurring patterns, correlations, and strategic design directions emerging from these implementations. Table 2 presents the cases collected for active packaging, while Table 3 presents the cases collected for intelligent packaging.

	Case Study Name	Company	Country	Year	Technology Type	Packaging Level	Application Field	Solution Aim
1	**AGELESS™**	Mitsubishi Gas Chemical Co. Ltd	Japan	1997	Oxygen scavenger	Primary	Food Arts and Culture Pharmaceuticals / Health Consumer Electronics	Prolong product shelf-life
2	**FreshMax®**	Multisorb Technologies, Inc.	USA	-	Oxygen scavenger	Primary	Food	Prolong product shelf-life
3	**Oxyguard® containers**	Toyo Seikan Kaisha Ltd.	Japan	-	Oxygen scavenger	Primary	Food Beverage Pharmaceuticals / Health Cosmetics / Personal Care	Prolong product shelf-life
4	**SHELFPLUS® O2**	ALBIS PLASTIC	Switzerland	-	Oxygen scavenger	Primary	Food, Beverage, Pharma/Health Cosmetics/Personal Care Home Care	Prolong product shelf-life
5	**DAREX®**	Henkel	Germany	2017		Primary	Beverage	Prolong product shelf-life
6	**ZerO2®**	Food Science Australia	Australia	-	Oxygen scavenger	Primary	Food, Beverage	Prolong product shelf-life
7	**ZerO2 Cap**	CARLSBERG	Denmark	2019	Oxygen scavenger	Primary	Beverage	Prolong product shelf-life Instructions for Use Reuse and End-of-Life Management

8	**CRYOVAC® BDF®**	Sealed Air	USA	-	Oxygen & Moisture absorber	Primary	Food	Prolong product shelf-life User Social and Environmental Awareness Instructions for Use Reuse and End-of-Life Management
9	**ATCO®**	Standa Industrie	France	-	Oxygen scavenger	Primary	Food Pharmaceuticals / Health	Prolong product shelf-life
10	**ATCO® BOX**	EMCO Packaging Systems	UK	-	Oxygen scavenger	Primary	Food	Prolong product shelf-life
11	**ATCO® Carbon Dioxide Absorbers Sachets**	EMCO Packaging Systems	UK	-	Carbon dioxide scavenger	Primary	Food Beverage Gardening	Prolong product shelf-life
12	**ATCO® IL**	EMCO Packaging Systems	UK	-	Oxygen scavenger Carbon dioxide emitter	Primary	Food, Pharmaceuticals / Health	Prolong product shelf-life
13	**OxyFresh™ Sachets**	EMCO Packaging Systems	UK	-	Carbon dioxide scavenger Oxygen emitter	Primary	Food Pharmaceuticals / Health Gardening	Prolong product shelf-life
14	**OMRI LISTED Super Fresh Media Sachets**	Ethylene Control, Inc.	USA	2020	Ethylene scavenger Odour absorber Antimicrobial agent	Primary	Food Gardening	Preserve during transport
15	**BION Ethyl Stopper**	EMCO Packaging Systems	UK	-	Ethylene scavenger	Primary	Food	Prolong product shelf-life
16	**KIF Sachet**	Keep It Fresh	India	-	Ethylene scavenger Moisture absorber Antimicrobial agent	Primary	Food Gardening	Preserve during transport
17	**BEfresh Technology**	Kerako Ceramic Technologies	Spain	-	Ethylene scavenger Moisture absorber Antimicrobial agent	Primary	Food Gardening	Preserve during transport

18	**BEfresh Home**	Kerako Ceramic Technologies	Spain	-	Ethylene scavenger Moisture absorber Antimicrobial agent	Primary	Food	Preserve during transport
19	**Ethylene Remover**	Shenzhen Chunwang New Materials Co., Ltd.	China	-	Ethylene scavenger	Primary	Food	Preserve during transport
20	**Antimold-Mild®**	Freund Corporation	Japan	-	Ethanol emitter	Primary	Food	Prolong product shelf-life
21	**Negamold®**	Freund Corporation	Japan	-	Oxygen scavenger Ethanol emitter	Primary	Food	Prolong product shelf-life
22	**HI-DE CAN**	Toyo Seikan Kaisha Ltd.	Japan	-	Moisture absorber	Primary	Food	Prolong product shelf-life
23	**IntelliSorb®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Pharmaceuticals / Health	Prolong product shelf-life
24	**CILICANT ACCUFLIP**	CINICANT ACTIVE PACKAGING	India		Moisture absorber	Primary	Pharmaceuticals / Health	Prolong product shelf-life
25	**TranSorb®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Tertiary	Logistics Shipping and Delivery	Preserve during transport
26	**DesiMax®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Pharmaceuticals / Health Consumer Electronics	Prolong product shelf-life
27	**Drikette®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Food	Prolong product shelf-life
28	**SaniSorb®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Pharmaceuticals / Health	Waste Disposal Optimization
29	**Polysorb®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Consumer Electronics	Preserve the product
30	**StabilOx®**	Multisorb Technologies, Inc.	USA	-	Moisture absorber	Primary	Pharmaceuticals / Health	Prolong product shelf-life

31	**Dri-Fresh Fresh-Hold™ OA**	Sirane Group	UK	-	Moisture absorber Odour absorber	Primary	Food	Prolong product shelf-life
32	**CILICANTFG ACTIVATED CARBONR**	CINICANT ACTIVE PACKAGING	India	-	Odour absorber Flavour emitter	Primary	Pharmaceuticals / Health	Prolong product shelf-life
33	**+42°**	The 42 Degrees Company	Spain	-	Self-heating	Primary	Beverage	Optimum consumption temperature Optimise preparation time Ready to be consumed
34	**Push & Drink**	Leonardos srl	Italy	-	Self-heating	Primary	Beverage	Optimum consumption temperature Optimise preparation time Ready to be consumed
35	**Pocket Bar Auto-Riscaldante**	Pocket Bar	Italy	.	Self-heating	Primary	Beverage	Optimum consumption temperature Optimise preparation time Ready to be consumed
36	**Gogol-Mogol**	KIAN	Russia	2011	Self-heating	Primary	Food	Ready to be consumed
37	**Self-Chilling Can**	ICTech	South Korea	2018	Self-cooling	Primary	Beverage	Optimum consumption temperature Optimise preparation time Ready to be consumed
38	**Pocket Bar Auto-Raffreddante**	Pocket Bar	Italy	-	Self-cooling	Primary	Beverage	Optimum consumption temperature Optimise preparation time Ready to be consumed

39	**Self-Cooling Cosmetics Container**	ICTech	South Korea	2018	Self-cooling	Primary	Cosmetics / Personal Care	Optimum consumption temperature Optimise preparation time Ready to be consumed
40	**Apeel**	Apeel	USA	2019	Modified Atmosphere Packaging	Primary	Food	Prolong product shelf-life Preserve the product during transport
41	**XgoTM**	j-tech systems	UK	-	Modified Atmosphere Packaging	Primary	Food	Prolong product shelf-life Preserve the product during transport
42	**Intelimer™ Tape Wax Substitute type**	Nitta	Japan	-	Temperature Compensating Films	Primary	Consumer Electronics	Product Preparation Optimisation Environmental Condition Monitoring
43	**Matter**	Matter	USA	2020	Antimicrobial Agent	Primary Secondary	Consumer Electronics Food Bevarage Fashion Pharmaceuticals / Health Logistics Shipping and Delivery	Product safety and hygiene
44	**SANICO®**	Standa Industrie	France	-	Antimicrobial Agent	Primary	Food	Prolong product shelf-life

Table 2. Case collected for intelligent packaging

	Case Study Name	Company	Country	Year	Technology Type	Packaging Level	Application Field	Solution Aim
1	**Innoscentia Label**	Innoscentia	Sweden	2022	QR Codes Gas Sensor Biosensor	Primary	Food	Brand System Information Product Impacts Information
2	**Star Wars Coca Cola Limited Edition**	Coca Cola and Inuru	Singapore	2020	Touch Sensors	Primary	Beverage	User Engagement Gamification and Reward System

3	**FACT Water**	Crown & Olly Bolton	USA	2018	QR Codes Blockchain	Primary	Beverage	User Engagement Gamification and Reward System Brand System Information Product Impacts Information
4	**O'air**	Deeez.co	UK	2021	QR-Codes AR/WebAR Codes	Primary	Pharmaceuticals / Health	User Social and Environmental Awareness
5	**Sustainable HF RFID Assisted E-fulfilment Package**	Buonamici, La Ranocchiaia, SPO and Il Cavallino	Italy	2014	NFC Tags	Primary	Food	Product Characteristics Information / Digital ID Counterfeiting Protection
6	**Remi Martin Club**	Remi Martin	France	2015	NFC Tags	Primary	Beverage	Product Impacts Information Theft Protection
7	**Delage Bag**	Delage & Inside Secure	France	2014	NFC Tags	Primary	Fashion	Product Characteristics Information / Digital ID Theft Protection
8	**Tapp Smart Sticker**	Cambridge Consultants	UK	2018	NFC Tags	Primary	Pharmaceuticals / Health	Product use and monitoring
9	**Cambio Coffee**	Mitsubishi Gas Chemical Co. Ltd	Japan	1997	QR Codes	Primary	Food	Logistics, Transport and Storage Optimisation Brand System Information Tracking and Traceability
10	**One Look**	Cymmetrik	China	2023	Digital Watermarks	Primary	Food	Logistics, Transport and Storage Optimisation Product Conditions and Quality Monitoring Tracking and Traceability

11	**WarmMark**	Warmmark ®	USA	/	Time Temperature Indicators (TTIs)	Primary	Food Pharmaceuticals/Health	Logistics, Transport and Storage Optimisation Environmental Conditions Monitoring
12	**FreezeSafe Indicator**	SpotSee	USA	/	Freeze Indicators	Secondary Tertiary	Food Pharmaceuticals/Health	Logistics, Transport and Storage Optimisation Environmental Conditions Monitoring Product Preservation
13	**ShockWatch 2 Impact Indicators**	/	USA	/	Barcodes	Tertiary	Indefinite Sector	Product Impacts Information Product Conditions and Quality Monitoring
14	**FreshTag Smart Labels**	Insignia Technologies	UK	/	Freshness Indicators	Primary	Food	Logistics, Transport and Storage Optimisation Product Quality Monitoring Counterfeiting Protection
15	**After Opening Timers**	Insignia Technologies	UK	/	Time Temperature Indicators (TTIs)	Primary	Food, Pharmaceuticals/Health	Logistics, Transport and Storage Optimisation Product Conditions and Quality Monitoring
16	**Leak Detection Label**	Insignia Technologies	UK	/	Gas Indicator / Gas Leakage Indicators	Primary	Food	Product Conditions and Quality Monitoring
17	**ESL SMARTpack**	EBV Elektroink	UK	2014	NFC Tags Temperature Sensor/Thermochromic Inks	Primary	Pharmaceuticals / Health	User Engagement, Gamification and Reward System Tracking and Traceability Theft Protection
18	**BAT-LYFT**	SharpEnd	UK	2021	NFC Tags	Primary	Arts and Culture	User Engagement

								Gamification and Reward System
19	**Shazam x Bombay Sapphire**	Bombay Sapphire	UK	2018	AR/WebAR Codes	Primary	Beverage	User Engagement Gamification and Reward System Brand System Information
20	**Christmas ARPackaging**	The Good Crisp Co. & Aircards	USA	2020	AR/WebAR Codes	Primary	Beverage	User Engagement Gamification and Reward System Brand System Information Product Impacts Information
21	**Tostitos**	Tostitos	USA	2018	NFC Tags Gas Sensor	Primary	Beverage, Pharmaceuticals/Health Consumer Electronics	User Engagement Gamification and Reward System Product Impacts Information
22	**AR Delivery Boxes**	Amazon	USA	2020	AR/WebAR Codes	Secondary	Logistics, Shipping and Delivery	User Engagement Gamification and Reward System
23	**BlindSpotz™ Freeze Indicator**	CTI	USA	/	QR Codes, Temperature Sensor / Thermochromic Inks	Primary	Pharmaceuticals / Health	Product Conditions and Quality Monitoring
24	**Reveal Impact**	Ardagh Group	Luxembourg	2017	Temperature Sensor / Thermochromic Inks	Primary	Beverage	Product Conditions and Quality Monitoring User Social and Environmental Awareness
25	**TempSafe Electrocard**	Ynvisible & SpotSee	Canada, USA	2021	QR Codes Temperature Sensor / Thermochromic Inks	Secondary	Logistics, Shipping and Delivery	Product Conditions and Quality Monitoring
26	**Gas Sensor**	MIT University	USA	2014	NFC Tags	Primary	Food	Product Conditions

					Electronic / Conductive Inks		Logistics, Shipping and Delivery	and Quality Monitoring
27	**Sneakers Authenticity Guarantee**	eBay & Sneaker Con	Germany	/	NFC Tags	Primary	Fashion Logistics, Shipping and Delivery	Counterfeiting Protection
28	**Pepsi Super Bowl LV 2021 Cans**	Pepsi	USA	2021	AR/WebAR Codes	Primary	Beverage	User Engagement Gamification and Reward System
29	**Tuned Wines**	DJ Jordi Ruz	Spain	/	NFC Tags	Primary	Beverage	User Engagement Gamification and Reward System
30	**Moose Knuckles Platform**	Moose Knuckles	Canada	/	RFID Tags NFC Tags	Primary (Label)	Fashion	User Social & Environmental Awareness Instructions for Use Reuse and End-of-Life Product Characteristics / Digital ID Brand System Info Product Impacts Information
31	**BVLGARI Platform**	BVLGARI	Italy	2023	NFC Tags	Primary (Product)	Fashion	User Social and Environmental Awareness Product Characteristics / Digital ID Brand System Information Counterfeiting Protection
32	**Ocean Bottle**	The Ocean Bottle Ltd	USA	2019	NFC Tags	Primary (Product)	Beverage	Product Characteristics / Digital ID Brand System Information Product Impacts Information User Social and Environmental Awareness

33	**Napolina Tomatoes Can**	Princes Group	Italy	2020	QR-Codes	Primary	Food	User Social and Environmental Awareness Instructions for Use Reuse and End-of-Life Management Product Characteristics / Digital ID Brand Info Product Impacts Information
34	**Mousline**	Nestlé & Carrefour	France	2019	QR-Codes Blockchain	Primary	Food	User Social and Environmental Awareness Instructions for Use Reuse and End-of-Life Management Brand System Info Product Impacts Information Traceability
35	**Medical Prescription**	Faller Packaging	Germany	/	Electronic / Conductive Inks Display (LED, E-Paper)	Primary	Pharmaceuticals / Health	User Accessibility Improvement Instructions for Use Reuse and End-of-Life Management
36	**PluggyMed**	Palladio Group	Italy	2021	Electronic / Conductive Inks IoT	Primary	Pharmaceuticals / Health	User Accessibility Improvement Instructions for Use Reuse and End-of-Life Management
37	**Farmison & Co Label**	Farmison & Co	UK	2023	QR-Codes	Primary	Food	User Social and Environmental Awareness Instructions for Use Reuse and End-of-Life Management

38	**SmartID**	Fraunhofer	Germany	2023	Barcodes	Primary	Pharmaceuticals / Health	Counterfeiting Protection
39	**Digi-Cap Closure**	Berry Global	USA	/	NFC Tags Temperature Sensor / Thermochromic Inks	Primary	Pharmaceuticals / Health	User Accessibility Improvement Product Conditions and Quality Monitoring
40	**Coca-Cola Christmas Pack with NaviLens**	Coca Cola UK with NaviLens	UK	2022	QR-Codes	Primary	Beverage	User Accessibility Improvement
41	**Sustainable HF RFID Assisted E-fulfilment Package**	Hasselt University	Belgium, Germany	2021	RFID Tags	Tertiary	Waste Management	Waste Disposal Optimisation Tracking and Traceability
42	**Fresh Label**	Naoki Hirota	Japan	2008	Barcodes Freshness Indicators	Primary	Food	Product Conditions and Quality Monitoring
43	**HolyGrail 2.0**	Greiner Packaging	Denmark, Germany, France	2022	Digital Watermark	Primary	Food, Beverage	Waste Disposal Optimisation User Social and Environmental Awareness
44	**YNAP Digital ID for Garment**	YNAP	Italy	2020	Digital ID QR Code	Primary	Fashion	Waste Disposal Optimisation Instructions for Use Reuse and End-of-Life Management Tracking and Traceability

Table 3. Case collected for intelligent packaging

4.1 Smart Packaging Main Applications.

The 88 collected case studies (44 for active packaging and 44 for intelligent packaging) are predominantly concentrated in three countries: the United States, Japan, and the United Kingdom—particularly for active packaging—while intelligent packaging cases are mainly from the United States and the United Kingdom. The analysis shows that primary packaging is especially relevant in three sectors: food, beverage, and pharmaceuticals/health products (see Figure 3). Among the 44 cases of intelligent packaging identified, 39 involve primary packaging. A small subset of these explores more advanced applications, such as direct integration into the product or product label. Notably, one of them is related to the fashion industry. It involves QR codes and NFC tags applied to the product label to enhance authentication, enable tracking and tracing, and communicate the circularity attributes of the garment. Another fashion-related case explores using embedded NFC tags in accessories, such as bags, which trigger personalised digital experiences when users interact via smartphones. In this instance, each product is linked to a unique Digital Product ID that activates tailored content based on contextual factors like user location, time, and device. This solution enables differentiated communication for consumers and sales personnel alike. It unlocks exclusive digital content post-purchase, establishing an ongoing channel between the brand and the customer throughout the product's lifecycle.

In contrast, secondary and tertiary packaging are far less represented: only two intelligent packaging cases involve secondary packaging, and one applies to both secondary and tertiary level of packaging. Similarly, in the 44 cases of active packaging examined, 43 were primary packaging. One example of tertiary application is present, along with a single antimicrobial coating solution applicable to both primary and secondary packaging. This distribution confirms a dominant trend: intelligent and active technologies are currently concentrated at the primary packaging level, where they offer the most significant potential for direct interaction, product protection, and value-added communication—particularly relevant in sectors like fashion where storytelling, authenticity, and material integrity are strategic priorities.

Smart packaging applications in the food, beverage, and pharmaceutical sectors can improve product safety, extend shelf life, and enhance consumer interaction. Smart packaging can represent an innovative tool in the fashion industry as well. For instance, integrating smart tags, embedded chips, and augmented reality (AR) technologies can provide consumers with a personalised shopping experience. Packaging can offer traceability data, information about material sources, and care instructions, enhancing transparency and brand credibility. Furthermore, smart packaging can connect with mobile devices to deliver virtual try-ons, styling suggestions, and other value-added services, enriching the consumer's experience.

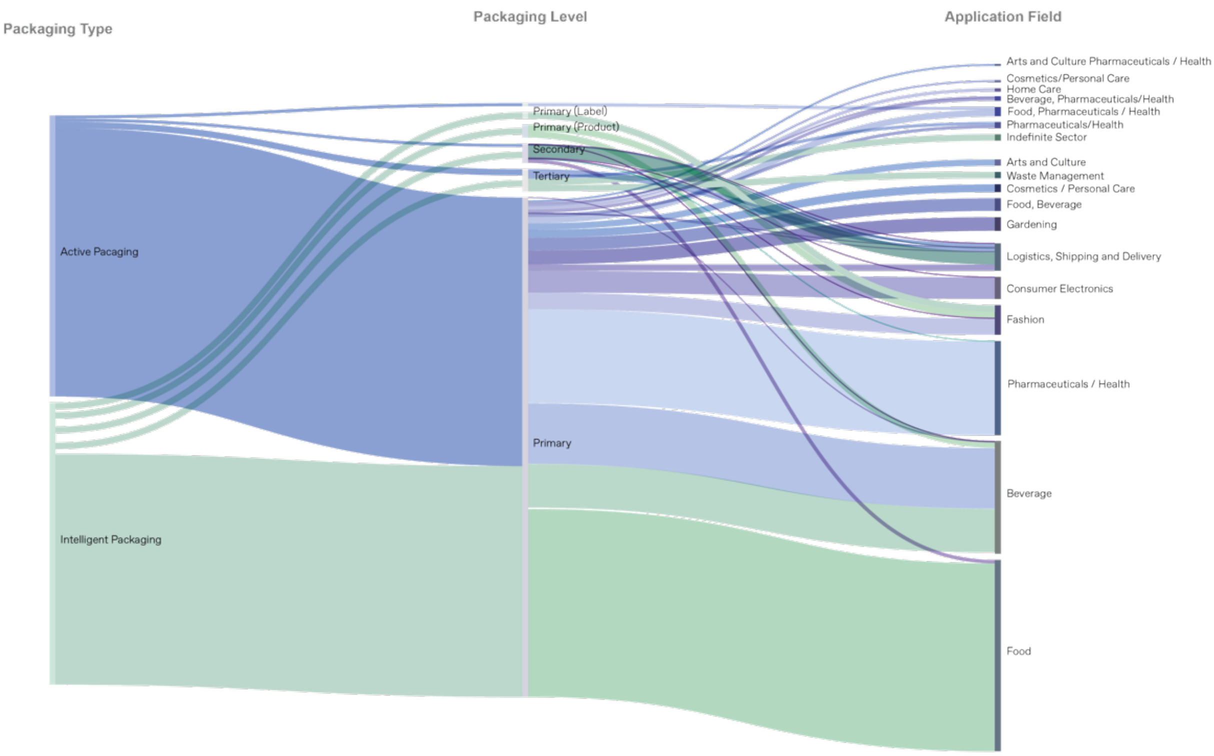

Figure 3. Main application of active and intelligent packaging. Source: author's elaboration.

4.2 Core Functions and Applications of Intelligent Packaging.

The analysis shows that the main technologies used in intelligent packaging are NFC (Near Field Communication), QR codes, and AR codes (see Figure 4). These offer different benefits, and their applications span multiple sectors.

NFC use appears in the beverage, fashion, and food industries. Its strength is enabling seamless, contactless interactions between packaging and digital content, supporting consumer engagement, authentication, and real-time data sharing. In the fashion industry, NFC helps protect brand integrity, verify authenticity, enhance product storytelling and provide care instructions.

QR codes are widely adopted, especially in food and beverage. Their ease of use allows consumers to access nutritional info, recipes, origin data, or marketing content via smartphone. In the fashion sector, QR codes can enable access to exclusive content such as virtual fashion shows, brand storytelling, and styling guides, enhancing consumer interaction.

AR codes, though less common, are gaining relevance in beverage and logistics. They offer immersive experiences, transforming packaging into interactive platforms. In logistics, they enable real-time inventory tracking. For the fashion industry, AR codes represent an innovative opportunity to engage customers through virtual try-ons, interactive catalogues, and augmented shopping experiences that blend the digital and physical. These technologies improve product information and engagement and reinforce authenticity, safety, and traceability. In fashion, they could support brand heritage, boost trust, and open new scenarios for consumer interaction.

The analysis identifies several key purposes of intelligent packaging technologies: user engagement, gamification, reward systems, social and environmental awareness, product condition and quality monitoring. NFC tags and QR codes support user engagement and gamification, enabling access to exclusive content, loyalty programs, and interactive campaigns, thus improving brand experiences. Moreover, brands can disclose sustainability efforts, ethical sourcing, and environmental impacts through QR codes and NFC tags.

In fashion, these technologies can communicate to the user the use of sustainable materials, fair labour practices, and initiatives to reduce environmental impact, enhancing brand reputation and consumer trust.

Lastly, intelligent packaging can monitor product conditions using sensors (e.g., temperature, gas indicators), QR codes, and NFC tags, ensuring in real-time integrity and freshness across the supply chain. In fashion, this real-time monitoring can ensure products preservation throughout logistics.

The analysis highlights how NFC, QR, and AR/WebAR codes enhance user engagement through entertainment. NFC tags allow seamless interactions, delivering product info and verification, while QR codes give access to rich content. In fashion, QR codes can offer consumers exclusive access to digital experiences such as fashion shows, behind-the-scenes content, or style guides, deepening their connection to the brand.

AR/WebAR codes enhance the interactive experience, making packaging a tool for augmented reality interactions. For fashion, this means virtual try-ons and immersive catalogues—transforming packaging into an extension of the brand experience.

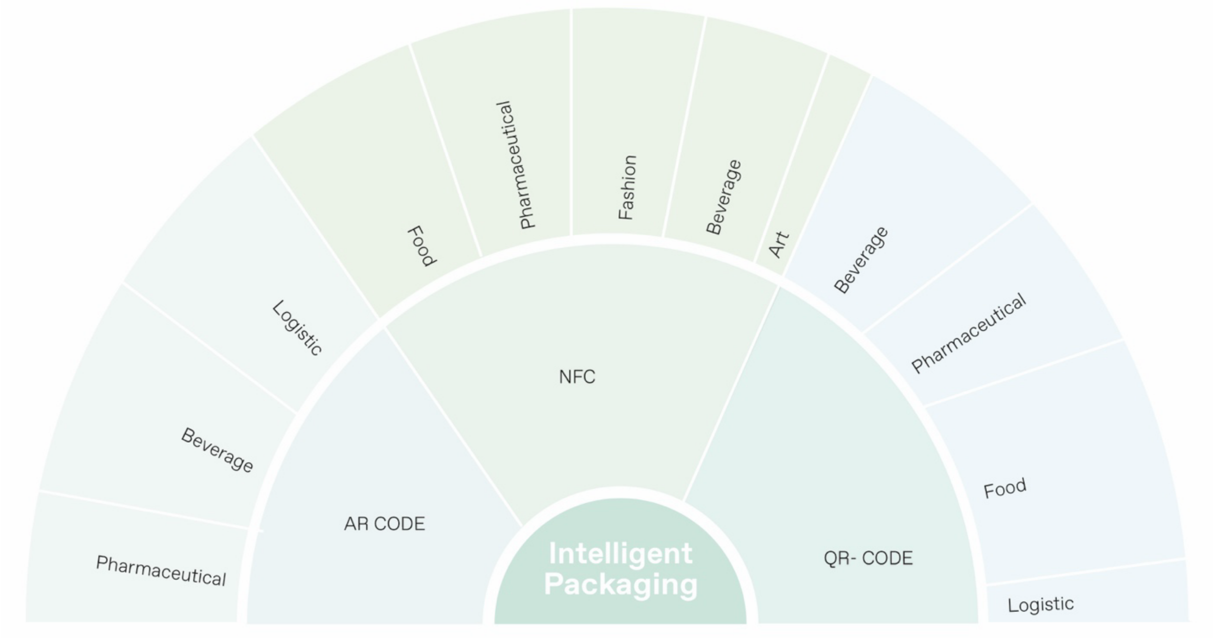

Figure 4. Main technologies used in intelligent packaging and their field of application. Source: Author's elaboration.

4.3 Core Functions and Applications of Active Packaging.

Active packaging uses key technologies such as moisture scavengers, oxygen scavengers, and self-heating/self-cooling systems, which are essential to product quality and safety (see Figure 5).
Moisture scavengers manage humidity, especially in food and pharma, preserving freshness and medication stability. Oxygen scavengers are applied in food and beverages to prevent oxidation and spoilage. In fashion, these could protect sensitive textiles and treatments from degradation.
Self-heating and self-cooling packaging, although niche, allow products, especially beverages and foods, to be consumed at ideal temperatures. These technologies add value in terms of convenience. They could be imagined in high-end fashion retail or e-commerce contexts (e.g., warming textiles, climate-sensitive packaging) as part of an exclusive experience.
The analysis illustrates the two core objectives of active packaging: extending shelf life and protecting products during transport.
Technologies like oxygen and moisture scavengers help prevent oxidation and maintain freshness, which is particularly relevant in food distribution, especially for delicate or luxury items.
Active packaging mitigates temperature variations, humidity, and shocks using antimicrobial agents and ethylene scavengers. In fashion, this applies to protecting materials susceptible to changes in temperature and humidity or premium materials, thereby supporting both quality and brand value.

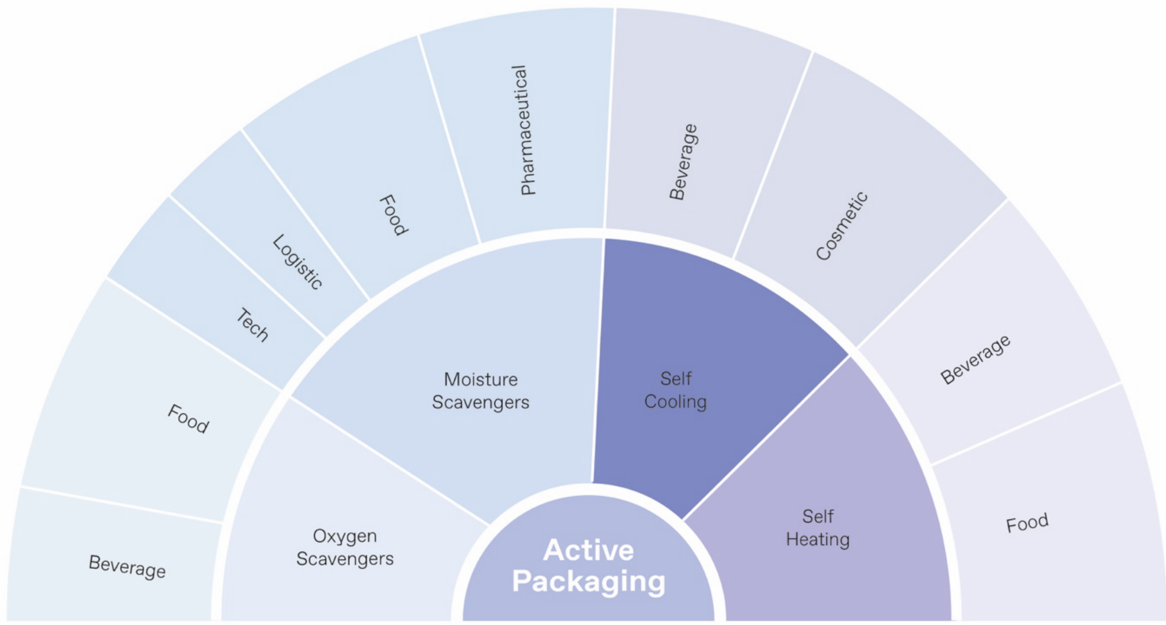

Figure 5. Main technologies used in active packaging and field of application. Source: Author's elaboration.

4.4 Smart Packaging in the Framework of EU Sustainability Policies.

The policy analysis conducted in this study highlights the strategic role of packaging, particularly smart packaging, within the broader framework of European sustainability goals. Regulations targeting packaging are not isolated measures but reflect a holistic approach outlined by the European Green Deal (2019), which sets the EU on a path toward climate neutrality by 2050. The Circular Economy Action Plan (2020) positions packaging as a priority sector for reducing waste, promoting reuse, and improving recyclability. Building on this, the Ecodesign for Sustainable Products Regulation (2022) introduces performance and information requirements to increase product sustainability across the EU market. A key component of this regulation is the Digital Product Passport (DPP), designed to share lifecycle data and support circular practices. Smart packaging technologies, such as QR codes, NFC tags, and RFID chips, can serve as enablers of the DPP. These tools make it possible to communicate real-time information about material composition, recycling options, and reuse potential. Their integration into packaging contributes to DPP implementation and greater transparency for regulators and consumers. The proposed Packaging and Packaging Waste Regulation (2022) further reinforces these objectives. It sets clear targets for waste reduction, reuse, and recyclability. Digital tools embedded in packaging can help meet these targets by offering consumers precise disposal instructions and traceable sustainability data. Recent initiatives such as the Directive on Empowering Consumers for the Green Transition (2023) and the Right to Repair underline the importance of accessible product information. Packaging can deliver this information directly to users through smart interfaces, enabling more conscious and responsible consumption choices. From this perspective, the role of packaging evolves from a micro-scale intervention to a macro-scale driver of change, serving as a bridge between product design, consumer behaviour, and environmental policy through digital integration. Figure 6 outlines the main policies in a hierarchical relationship.

Figure 6. Main policy regulation at European level. Source: Author's elaboration adapted from Tichoniuk (2023)

5 Conclusions

Given the increasing environmental and social impact generated by the fashion sector, it is crucial to understand how we can leverage packaging as a vector of circularity and transparency, exploiting digital technology advancements. Through a comprehensive investigation, comprising a literature review, an in-depth case study analysis, and a focused policy review, this study identifies the key potentialities of smart packaging in supporting a sustainable transition of the fashion supply chain.

The analysis reveals how digital technologies, developed initially and widely implemented in sectors such as food and pharmaceuticals, are opening potential applications within the fashion domain. These systems extend beyond functional roles such as product preservation and logistics optimisation to enable enhanced communication, user engagement, and value creation aligned with sustainability goals.

In the context of fashion, the findings highlight how smart packaging can be adapted to serve multiple functions, ranging from product traceability and authenticity verification to storytelling, transparency, and interactive brand experiences. The case study analysis demonstrates that technologies such as NFC tags and QR codes ensure product traceability, verify authenticity and enable interactive storytelling. They can provide transparent, real-time information on origin, materials, care instructions, and ethical claims, enhancing consumer trust and reinforcing brand reputation. AR and WebAR technologies generate immersive brand experiences, from virtual try-ons to augmented catalogues. These experiences transform the packaging into a dynamic interface connecting the physical and digital dimensions, enhancing brand engagement and differentiation. Adopting intelligent packaging with embedded sensors and indicators enables continuous monitoring of product conditions throughout the supply chain. In fashion, this is especially useful for preserving the integrity of delicate or high-end materials, contributing to waste reduction and quality assurance.

Although still emerging, active packaging solutions, such as self-regulating temperature systems and protective scavengers, demonstrate potential in luxury and e-commerce contexts, where they can support the conservation of sensitive materials and elevate customer experience during delivery and unboxing.

While the present study maps the existing technological scenario and highlights key opportunities, further research is needed to investigate the integration of these technologies within design processes, supply chain models, and consumer behaviours in fashion.

The policy analysis conducted in this study provides a contextual framework for understanding the potential of the new role of packaging in enhancing more circular supply chains. The packaging-as-broadcaster concept presents a novel regulatory and commercial opportunity. However, integrating digital technology into physical packaging reveals critical contradictions and trade-offs. Chief among these challenges is ensuring recyclability. While digital components facilitate data-rich interactions, they can also complicate post-consumer material sorting and compromise the recyclability of packaging, particularly in fibre-based systems. For instance, integrating sensors or conductive inks within paperboard substrates may result in heterogeneous material streams, which can compromise the efficacy of recycling processes and contaminate paper recovery cycles. Furthermore, the environmental impact of post-disposal electronics necessitates rigorous scrutiny. Even if minimal in size, the deployment of digital tags and chips raises questions regarding electronic waste management and the energy footprint of data storage and transmission servers. If these factors are not addressed, the environmental gains achieved through enhanced circularity could be nullified.

Integrating technologies such as RFID, NFC, sensors, or blockchain-enabled smart labels into packaging brings opportunities and trade-offs. The advantages of these solutions include enhanced traceability, improved product safety, extended shelf life, and reduced food waste. In some cases, these benefits can outweigh the environmental impact of the added electronics (Stramarkou et al., 2022; Ahamed et al., 2024). However, the feasibility of such systems is often contingent on cost considerations. Specifically, passive or printed tags are relatively affordable at scale, while sensorised or active systems remain expensive and are better suited for high-value or perishable goods (Zikulnig et al., 2025). Concurrently, sustainability challenges emerge. Incorporating components such as chips, antennas, or batteries introduces materials that complicate recyclability and risk creating electronic waste if packaging is disposed of with conventional waste streams (Hakola et al., 2024). Paper-based substrates and battery-free designs have the potential to mitigate some of these impacts; however, the absence of clear end-of-life strategies or take-back systems could hinder the realisation of circular economy goals (Ahamed et al., 2024; Zikulnig et al., 2025). Consequently, adopting such technologies necessitates a balanced consideration of short-term functional benefits and long-term environmental and economic implications.

Future studies should investigate the scalability and cost-efficiency of smart packaging solutions across diverse fashion segments, such as luxury, fast fashion, and second-hand markets, as well as user acceptance and interaction dynamics. Although these technologies show strong potential as enablers of a sustainable transition, further research is needed to assess their full environmental impact, particularly when integrated into packaging systems. It is essential to ensure that these innovations support circular economy goals effectively rather than creating new complexities or waste. Adopting a holistic perspective, including critically evaluating life cycle implications and potential side effects, will be crucial.

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