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# INTEGRATION OF EMERGING TECHNOLOGIES INTO SUPPLY CHAINS TO PROMOTE THE CIRCULAR ECONOMY

Rina ȚURCAN, conferențiară universitară, doctor în științe economice
ORCID: 0000-0002-6001-2025
Universitatea Tehnică a Moldovei, bd. Stefan cel Mare 168, Chisinau, Republica Moldova
rina.turcan@emin.utm.md

**Abstract.** The paper addressed a major topical issue - the integration of emerging technologies in agri-food chains as a solution to promote the circular economy and reduce resource wastage. The aim of the research was to highlight the transformative potential of these technologies in the context of the transition towards a sustainable and resilient agri-food system. Several objectives were formulated, including the identification of relevant key technologies, the analysis of implementation barriers and the highlighting of associated economic and environmental benefits. The research was based on methods of documentary analysis, theoretical synthesis and case studies from European and national practice. Following the analysis, it was found that technologies such as IoT, blockchain, artificial intelligence, robotics and biotechnologies contribute significantly to resource efficiency, product traceability and loss minimization along the value chain. At the same time, obstacles such as high costs, lack of digital skills and regulatory challenges were identified. The results can be used by actors involved in the agri-food sector in strategic decision making and provide a solid framework for future research dedicated to validating the impact of these technologies in ensuring sustainable development.

**Keywords:** emerging technologies, agri-food chains, circular economy, digitalization, sustainability, IoT and blockchain.

**Rezumat.** Lucrarea a abordat o temă de actualitate majoră – integrarea tehnologiilor emergente în lanțurile agroalimentare ca soluție pentru promovarea economiei circulare și reducerea risipei de resurse. Scopul cercetării a fost de a evidenția potențialul transformator al acestor tehnologii în contextul tranziției către un sistem agroalimentar sustenabil și rezilient. Au fost formulate mai multe obiective, printre care identificarea tehnologiilor-cheie relevante, analiza barierelor de implementare și evidențierea beneficiilor economice și de mediu asociate. Cercetarea s-a bazat pe metode de analiză documentară, sinteză teoretică și studii de caz din practica europeană și națională. În urma analizei, s-a constatat că tehnologii precum IoT, blockchain, inteligența artificială, robotica și biotehnologiile contribuie semnificativ la eficientizarea utilizării resurselor, trasabilitatea produselor și diminuarea pierderilor de-a lungul lanțului valoric. Totodată, au fost identificate obstacole precum costurile ridicate, lipsa competențelor digitale și provocările legislative. Rezultatele obținute pot fi utilizate de către actorii implicați în sectorul agroalimentar în luarea deciziilor strategice și oferă un cadru solid pentru cercetări viitoare dedicate validării impactului acestor tehnologii în asigurarea dezvoltării sustenabile.

**Cuvinte-cheie:** tehnologii emergente, lanțuri agroalimentare, economie circular, digitalizare, sustenabilitate, IoT și blockchain.

## Introduction

Circular economy proposes a sustainable development model by minimizing waste and saving resources for the longest possible time, in contrast to the linear "extract-produce-throw away" model [1]. In the agri-food sector, the adoption of circular principles is crucial, as approximately one-third of food worldwide is lost or wasted through the supply chain [2]. This situation not only represents an enormous waste of resources (water, soil, energy) but also contributes to significant greenhouse gas emissions and massive economic losses. International organizations, such as the FAO, advocate for building a sustainable and circular agri-food system that prevents food waste, reduces spoilage, keeps materials in circulation, and regenerates natural ecosystems.

In recent decades, emerging technologies have provided new opportunities for transforming agri-food supply chains in a circular sense. Digital transformations support the development of entrepreneurial performance by automating processes, providing rapid access to information, and expanding communication and sales channels, enabling firms to be more sustainable and compete more effectively in the international market [3]. Cutting-edge technologies, such as the (IoT), blockchain, Internet of Things (IoT), blockchain, artificial intelligence (AI), robotics, biotechnologies, and 3D printing, can be integrated across production, processing, and distribution to improve efficiency, traceability, and the reuse of resources [4]. IoT and connected sensors enable real-time monitoring of conditions, blockchain ensures traceability and confidence in product provenance, AI provides predictive analytics and optimization, robotics increases accuracy and reduces waste, biotech harnesses organic waste, and 3D printing facilitates on-demand packaging solutions and parts to support reuse.

Despite efforts to modernise agricultural production, farmers in the Republic of Moldova continue to face significant challenges in organising their supply chains, resulting in delays, losses, and low yields in fruit marketing [5]. This article examines emerging technologies, their use in agri-food chains and their impact on the circular economy, from reducing waste and reusing by-products to increasing traceability, energy efficiency and overall sustainability.

## 1. Relevant emerging technologies in agri-food chains

In a context marked by climate volatility, demographic pressures and sustainability imperatives, emerging technologies are becoming real vectors for transforming agri-food chains. They are no longer mere efficiency tools but underpin a new paradigm of circular functioning, where information, automation, and biological innovation enable the optimisation of resource use and the drastic reduction of losses. In this sense, agri-food chains are increasingly becoming smart infrastructures, capable of anticipating, responding and adapting in a systemic way to the requirements of a regenerative economy.

O highlight concretely how technology supports the transition towards circular and resilient agri-food chains, the most relevant emerging tools are presented below.

*1. Internet of Things (IoT) and smart sensors.* Internet of Things refers to the network of devices and connected sensors that are collecting and exchanging data over the Internet. In agriculture and the food industry, IoT encompasses environmental sensors (for temperature, humidity, light, and air quality), as well as machine and vehicle monitoring devices, smart tags, and other sensors along the supply chain [6]. IoT integration directly addresses the significant causes of waste in the food chain - lack of information and real-time control. Inefficiencies and lack of visibility at the production, storage and distribution stages lead to significant food waste [7]. IoT bridges these information gaps by collecting and communicating data throughout the 'food cycle', enabling prompt decisions to avoid waste. For example, continuous monitoring of storage conditions can provide an early warning of a refrigeration failure, allowing food to be moved before it spoils. Overall, the supply chain is becoming "smart" - data shared among farmers, processors, distributors, and retailers leads to greater efficiency in resource use and reduced waste of food and materials. Recent studies indicate that the widespread adoption of sensors and IoT systems can significantly reduce food waste while enhancing the efficiency of land, water, and energy use associated with production. [7]. n terms of the circular economy, IoT helps close feedback loops in the agri-food chain. Stock and quality data can facilitate the redirection of edible surplus to alternative markets or food banks before it becomes waste, and waste data can be used to optimise future processes. In addition, the transparency provided by IoT increases consumer confidence in sustainable products, stimulating demand for circular.

*2. Blockchain technology and food chain traceability.* Blockchain is a technology of distributed ledger that allows transactions and information to be stored in a transparent, secure, and immutable (non-reversible) manner. Data is divided into cryptographically linked blocks and replicated across multiple nodes, which prevents one-sided falsification of information. In the agri-food context, a blockchain can record all events in the supply chain,, from the lot harvested on a farm to processing and transportation and the supermarket shelf,, allowing all parties access to a common product history [8]. Blockchain facilitates full transparency and trust among actors in the agri-food chain, fostering collaboration and circular practices. Through traceability, points in the chain where losses or waste frequently occur can be identified, and specific preventive measures can be taken. At the same time, when a quality issue arises, the very short reaction time provided by blockchain means that non-compliant products can be quickly isolated, avoiding massive "blind" recalls and thus avoiding unnecessary waste of safe food [8].

*3. Artificial intelligence (AI) and data analytics.* Artificial intelligence includes a suite of technologies (machine learning, neural networks, heuristic algorithms, computer vision, etc.) that allow computing to process large volumes of data, to recognize patterns and make decisions or forecasts similar to human judgment [9]. In the agri-food chain, AI leverages the data collected (from IoT sensors, satellite imagery, and market data) to optimise processes and automate decisions, from farm level to supply chain management. Use in the agri-food chain: AI has diverse applications in agriculture and the food industry, helping to streamline and coordinate the entire chain, which is ensured through precision farming, crop prediction and inventory management, quality, sorting and intelligent processing, logistics and distribution, and surplus and waste redistribution [2], [10]. With its ability to manage complexity, artificial intelligence becomes a key driver of the circular economy in the food chain, maximising resource efficiency and minimising waste. AI enables the systemic optimisation of the supply chain, where each link is fine-tuned based on data to produce the required quantity at the optimal time with minimal resource consumption [2].

*4. Robotics and automation.* Robotics refers to the automatic, programmable use of machines, often equipped with artificial intelligence (AI), to perform physical tasks in place of humans. In the agri-food chain, robotics includes a wide range of technologies: autonomous agricultural machinery (tractors, harvesting or weeding robots), drones for monitoring and applying treatments, robotic arms and automated lines in processing plants, mobile robots in warehouses and logistics centres, and robots for waste management (e.g. robots that sort recyclable or organic waste). By increasing the accuracy, efficiency and consistency of operations, robotics acts as a key enabler to multiply the benefits of the circular economy in the agri-food chain. First and foremost, robots promote resource use efficiency. The precise application of inputs, complete processing of raw materials, and reduced waste in harvesting and processing translate directly into less waste generated and savings in natural resources [11].

*5. Biotechnologies and the circular bioeconomy.* Biotechnology encompasses techniques and technologies that utilise biological systems, living organisms, or their derivatives to develop products and processes [12]. In the agri-food sector, biotechnologies encompass the genetic improvement of crops and beneficial microorganisms, fermentation and industrial enzymatic processes, the cultivation of biomass for food or feed, and the development of biomaterials and biorefinery processes that transform biomass and organic waste into value-added products. The concept of the circular bioeconomy is at the intersection of circular economy and biotechnology, aiming at the integral and regenerative valorisation of biological resources and organic waste in productive cycles. Biotechnologies are a fundamental catalyst for the circular economy in the food sector as they directly address the transformation of waste into resources and the regeneration of biological systems [12]. Through them, organic waste becomes raw material, either for energy or for new products, practically realising the ideal "nothing is lost, everything is transformed". Such approaches increase the overall efficiency of the chain: not only is the amount of waste going to landfills reduced, but the need for virgin raw materials is also reduced as waste becomes an alternative source. The implementation of circular economy principles is becoming more and more relevant, helping to transform production waste into valuable resources and to make sustainable use of by-products [13].

*6. 3D printing. 3*D printing, commonly also known as additive production, is a process that produces a three-dimensional object by successive deposition of layers of material based on a digital model. This technology enables the rapid and flexible manufacture of customised components, prototypes or even finished products without the need for dedicated models or production lines[14]. In the agri-food chain, 3D printing is finding niche applications with potential impact on the circular economy through the possibility of producing on-demand spare parts, tools, or reusable packaging, as well as the emergence of food printing. Although 3D printing is not yet ubiquitous in agri-food chains, its potential for customisation, localised and on-demand production complements circular economy strategies. First, 3D printing contributes to extending the life cycle of products and equipment by manufacturing spare parts and repairing machinery locally. This approach avoids both the manufacture and transportation of parts from far away and the decommissioning of otherwise functional equipment. Secondly, the possibility of innovative reusable packaging leads to a reduction in single-use packaging and less product damage[14].

he adoption of emerging technologies can no longer be treated as an option but is a crucial and valuable condition for the viability of post-2030 agri-food chains. In a world in which resources are becoming increasingly rare and in which traceability and sustainability become competitive criteria traceability and sustainability are becoming criteria for competitiveness, these technologies offer a significant strategic advantage. The integration of modern technologies in developing countries, such as the Republic of Moldova, remains quite problematic, mainly due to the excessive fragmentation of the sector and the limited financial capacities of small producers [15]. The gradual adoption of digital technologies and innovative agriculture in the Republic of Moldova reflects a commitment to modernising the agricultural sector and increasing productivity in line with European standards [16]. Considering the benefits and impact of the tools presented, only innovative and coordinated integration of innovations can ensure the transition from a wasteful and linear food economy to a circular, resilient and value-centered one. That is why investments in digitisation, automation and bio-innovation are not only advisable but imperative.

**Transforming supply chains through emerging technologies and circular business models**

Emerging technologies are radically redefining supply chains, fundamentally transforming them from transactional structures into circular, intelligent and responsible ecosystems. Technologies such as blockchain, artificial intelligence and digital twins become catalysts for sustainability beyond their operational role, enabling traceability, resource efficiency and ESG compliance. This transformation differentiates reactive companies from transformative organisations, for which sustainability becomes a strategic criterion, not just an operational option.

Figure 1 shows a conceptual map of the transformational paradigm shifts in supply chains, highlighting the transition from traditional decision vectors to new strategic criteria that are fundamental in the transition to the circular economy era.

The diagram shown in Figure 1 is emblematic of how contemporary challenges are rewriting supply chain decision-making hierarchies. No longer are cost, quality, and level of service the canonical elements of operational efficiency at the centre of decision-making. However, the new imperatives are resilience, agility, and, above all, sustainability. This shift is not superficial; it reflects a realignment of values in the supply chain in response to a broad set of systemic shocks: geopolitical disruptions, resource shortages, ESG pressures, accelerated technological transformations, and acute skills shortages.

Technologies are not simply 'inputs' into existing processes; they become vehicles for systemic reconfiguration. Thus, blockchain supports the full traceability of raw materials, providing support for ESG criteria. AI and decision intelligence enable uncertainty management through predictive scenarios, thereby enhancing resilience. Digital twins underpin resource optimisation and close material loops in the logic of circularity.

Thus, one can observe a disjunction between reactive companies that remain anchored in the logic of transactional decisions and transformative organisations that internalise new decision vectors as part of a regenerative strategy. In this sense, sustainability is no longer an "additional driver", but becomes the condition for the validity of viable supply chains post-2030, charting a proposed strategic direction for the post-industrial era.

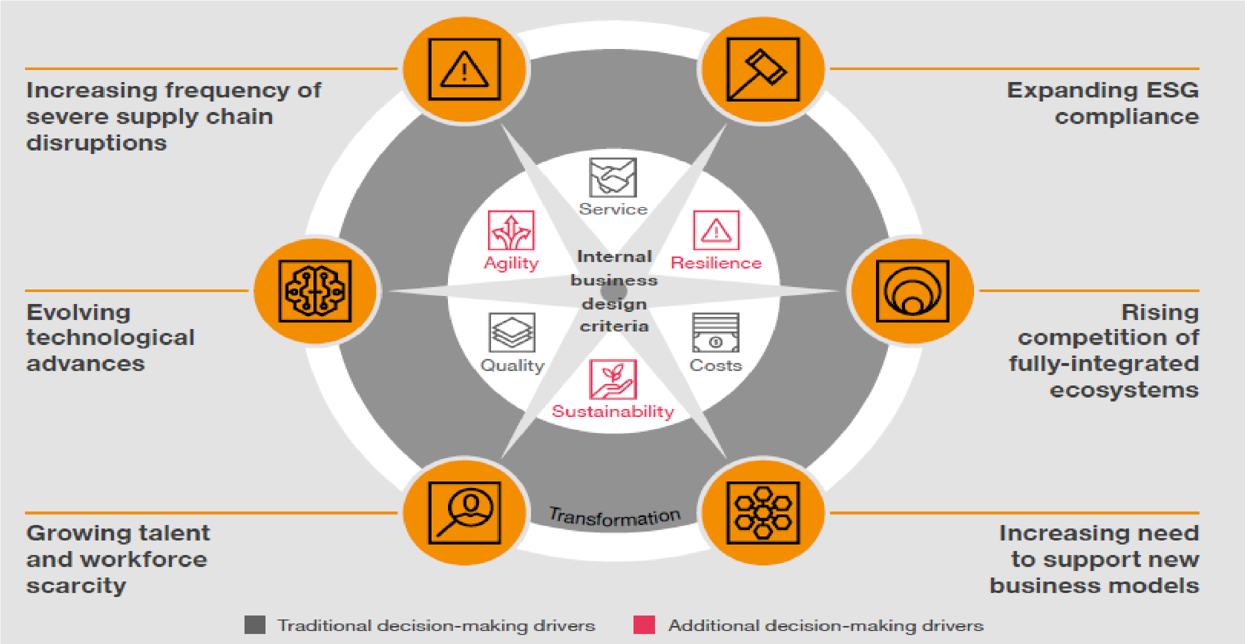


**Figure 1. An overview of emerging trends in supply chains and their impact on traditional and modern decision-making criteria**

*Source:* [17]

Figure 2 illustrates the level of readiness of companies to cope with the main disruptive trends in supply chains, comparing the responses of all companies with those of organisations considered "Champions," i.e., transformational leaders.

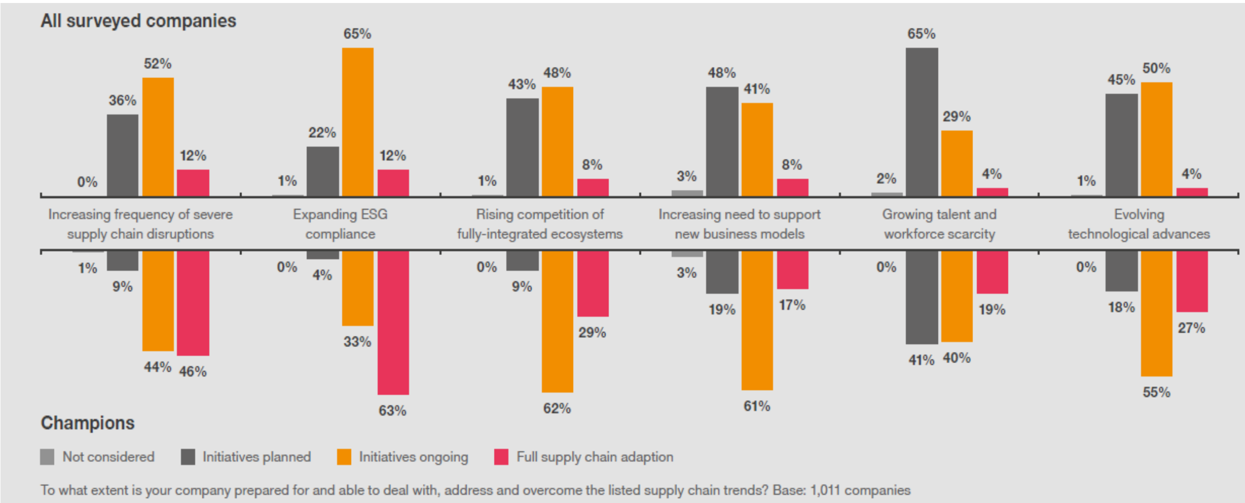


**Figure 2. Companies' readiness for emerging trends in supply chains: general perceptions versus transformational leaders**

*Source:* [17]

The visual analysis offers a differentiated perspective on the distinction between mainstream and advanced transformation companies. It shows that, among mainstream companies, the majority are at the "initiatives in progress" stage for the most pressing trends, such as ESG compliance (65%) and frequent supply chain disruptions (52%). In contrast, the percentage of those who have completed full supply chain adaptations is significantly lower (below 13% for all trends). In contrast, 'Champions' companies demonstrate an advanced degree of maturity: almost half have fully adapted their chains to respond to disruptions (46%) and ESG pressures (46%), while others have made notable progress on integrated ecosystems (29%) and adopting new business models (17%). These data indicate that industry leaders are taking a proactive, systemic and forward-looking approach.

In this way, it can be concluded that there is a clear gap between transformative and reactive companies, with a growing commitment to sustainability and digitalisation trends. The figure confirms that while most companies have recognised the multiple supply chain pressures, few have moved to complete transformative actions. The performance gap between the 'champions' and the rest of the companies suggests that only a clear strategy, based on the integration of emerging technologies and a circular economy focus, can ensure resilience and competitiveness in the long term.

Figure 3 presents the framework of an ESG (Environmental, Social, Governance) compliant supply chain, integrating compliance requirements, technological capabilities and examples of practical applicability throughout the whole supply chain, from supplier to customer.

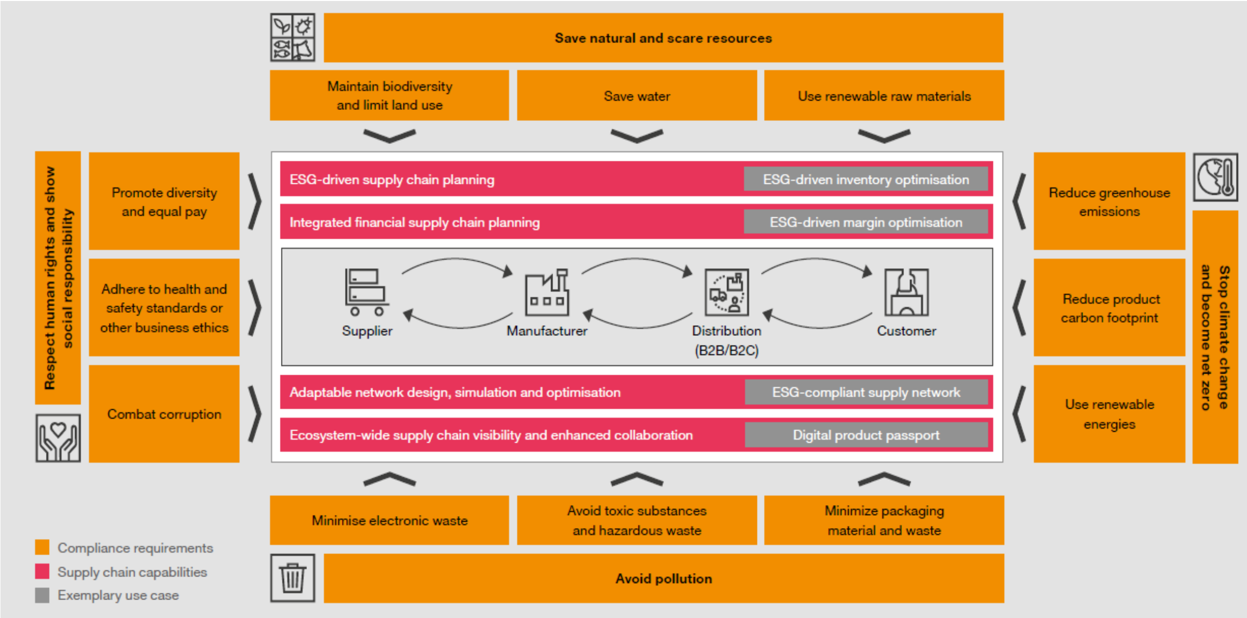


**Figure 3. Integrated framework for supply chain transformation in line with ESG principles and circular economy objectives**

*Source:* [17]

This systemic representation highlights a holistic view of supply chain transformation through the lens of ESG objectives. It is one of the most relevant figures in the context of integrating emerging technologies to support the circular economy. At its core are ESG-driven technological capabilities, such as ESG-based inventory planning and optimisation, ecosystem-wide visibility, or digital product passporting, all of which support transparency, traceability, and informed decisions.

By integrating these capabilities, it builds the foundations for an innovative, responsible and adaptable supply chain. A supply chain in which human rights, safety standards and diversity are respected, and logistics decisions are driven not only by economic efficiency but also by environmental and social impact. In this context, the digital product passport offers circular product traceability, facilitating reuse, remanufacturing and recycling processes as key to closing the loop in the circular economy model. Based on the above, it can be concluded that integrating emerging technologies into supply chains is not a luxury but a fundamental prerequisite for ESG compliance and the transition to circular models.

Figure 4 presents an overall conceptual picture illustrating the transformation of emerging business models in supply chains, highlighting the transition from traditional linear models to those based on circularity, reuse and services by depicting the physical and service flows associated with each model.

Figure 4 shows a general conceptual overview illustrating the transformation of business models in supply chains from traditional linear paradigms to more complex forms adapted to the logic of the circular economy. Through a precise sequence, it illustrates the evolution from modular ownership models, in which the product is manufactured, delivered and consumed without return in the flow, to models centred on services, sharing, reuse and eventually full reintegration into the production cycle. This progression reflects the shift from an economic model based on volume and consumption to one based on sustainable value and resource regeneration.

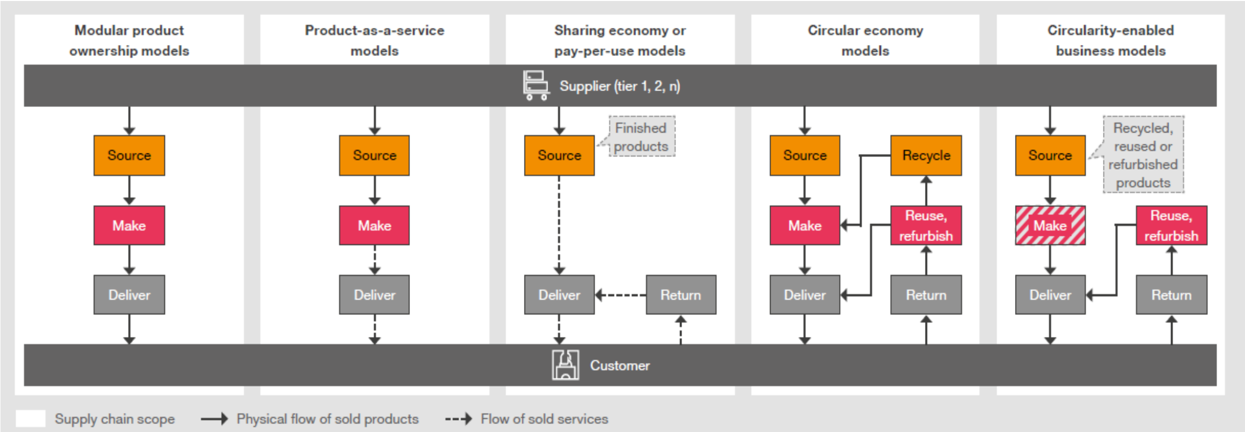


**Figure 4. Evolving business models in supply chains: from linear to circularity and service-based models**

*Source:* [17]

In the first stage, the make-deliver model is characterized by the definitive transfer of the product and the lack of a post-delivery relationship between the producer and the consumer. Although operationally efficient, this system generates massive material wastage, is limited in its scope for innovation and is increasingly incompatible with ESG requirements and sustainability objectives. In contrast, product-as-a-service models propose a fundamental shift, where the consumer becomes the user, and the manufacturer retains responsibility for the product throughout its life cycle. This approach not only extends the useful life but also enables the development of ancillary services, such as maintenance, upgrades, or end-of-life take-back, making the supply chain more flexible and maintaining customer interaction in the long term through a partnership.

The "sharing-economy" or "pay-per-use" models takes the separation of ownership and use a further step, favoring temporary access over possession. In this way it greatly reduces resource consumption and pressure on production. However, it requires a high-performance technological and logistical infrastructure capable of managing product turnover and ensuring real-time service quality. At this stage, the integration of emerging technologies, such as IoT, artificial intelligence, and blockchain, becomes critical for usage monitoring, product authentication, and traceability validation.

In this way, circular economy and fully circularity-enabled models are at the core of sustainable transformation. They involve not only returning products to the producer but also reusing, remanufacturing or recycling components and integrating them into new production cycles. Unlike other models, they require a systemic vision, advanced planning capabilities and a robust digital architecture. They actively integrate reverse workflows, shared databases, product condition assessment processes and a reuse-centric design strategy. The success of these models also depends on horizontal collaboration among ecosystem actors, including suppliers, distributors, recyclers, and customers, as well as the coherence of vertically applicable ESG policies. The transition to the circular economy cannot take place without a profound redefinition of business models and the way the supply chain is thought, designed and operated. Emerging technologies are not just optimization tools but become the critical infrastructure for regenerating economic and environmental value. Only by integrating them into chain architecture can circular models become scalable, economically viable and strategically relevant.

**Obstacles and challenges in implementing emerging technologies**

Although promising, the large-scale implementation of emerging technologies in agri-food chains is not without obstacles. Identifying and addressing these challenges is essential to accelerate the transition to a circular economy in the agri-food sector. The obstacles to implementation relate to both technical and economic factors (cost, infrastructure, standards) and human and institutional factors (skills, regulations, attitudes). The literature emphasises the importance of addressing these barriers through coordinated public policies and organisational strategies. The main barriers include the following:

- *High initial costs and access to capital.* Many emerging technologies (e.g., IoT devices, agricultural robots, biotechnology facilities) require significant initial investments, which are often difficult to afford, especially for small farms or small and medium-sized enterprises (SMEs) in the food industry. Studies report that the high cost of technological investments is perceived as a significant obstacle, as is the uncertainty regarding the payback period of these investments [1]. Even if they bring long-term savings, companies hesitate in the face of the immediate costs and perceived risk.
- *Insufficient digital infrastructure.* Implementing IoT and other solutions requires reliable internet connections in rural areas, GPS coverage, stable power grids and sometimes specialised infrastructure. The lack of communication infrastructure and basic equipment in rural areas or developing economies is a real barrier [1]. Without broadband networks and possibly 5G, many IoT and AI solutions cannot function optimally in agricultural areas. Also, logistics infrastructure (cold storage, sensor-equipped vehicles) may be missing or outdated, limiting the adoption of supply chain monitoring technologies.
- *Skills gap and resistance to change.* Technological adoption requires IT knowledge and new skills from farmers, managers and workers. In many regions, a digital skills gap exists – staff lack the knowledge to use and maintain new systems, resulting in reluctance. Furthermore, there is a cultural resistance to change. For example, a winegrower may distrust the recommendations provided by an AI algorithm for pruning the vine, preferring instead to rely on their own experience. The lack of adequate training and practical demonstrations reinforces this resistance. For companies, the fear of disrupting existing flows with new technologies can be a delaying factor.
- *Interoperability and standardization.* With the diversity of technical solutions available, the problem of the lack of common standards arises. Integrating IoT devices from different manufacturers into a single platform can be challenging; value chain databases may be incompatible, and data formats and quality can vary. The need for unified frameworks and standards is excellent – for example, one report highlighted that the lack of standards prevents the full realisation of blockchain's potential in agri-food [18]. Without standardisation, companies may be deterred from investing, fearing that the chosen solution will quickly become obsolete or fail to connect with their partners. Interoperability is also essential for sharing traceability data – if some use blockchain while others use traditional ERP systems, it is challenging for them to communicate effectively.
- *Data and cybersecurity concerns.* The digitalisation of the food chain involves the collection and sharing of an enormous amount of sensitive data, from recipes and processes to production data and even personal consumer information. Many companies fear that sharing data could make their competitive position vulnerable if the information falls into the hands of competitors or becomes public. There is also the risk of cyberattacks on critical infrastructure. Thus, a lack of trust in the security of new systems presents both psychological and practical obstacles. Strong cybersecurity measures and robust legal frameworks are necessary to alleviate these concerns.
- *Legislative and regulatory challenges.* Technological and business model innovations often outpace existing regulations, creating uncertainty. For example, food waste legislation can impede some forms of reuse, such as insect feeding for livestock, which is strictly regulated, and food donation has legal liabilities. The use of agricultural drones clashes with aerial and privacy

regulations. Even the use of blockchain data can raise GDPR compliance issues. Inconsistency and a lack of legislative clarity can discourage the adoption of new technologies, as actors fear penalties or investments that could be deemed non-compliant later [1].

Despite the transformative potential of emerging technologies to reconfigure agri-food chains circularly and sustainably, the analysis highlights a set of systemic barriers that hinder this process. The barriers identified, of an economic, technological, organisational and institutional nature, are not just operational impediments but reflect the deep gaps between the promise of innovation and the realities of implementation on the ground. High costs, lack of infrastructure, skills shortages and regulatory uncertainties are clear signals that technology, however advanced, is not sufficient in itself.

Overcoming these challenges requires a systemic, collaborative, and anticipatory approach, where public policies, institutional support, and cross-sectoral partnerships are integrated with investment in technology. Without coordinated and sustained interventions, the risk is that the benefits of circularity and digitisation will remain concentrated in the hands of isolated actors, and most agri-food chains will remain trapped in linear, fragile and wasteful models. This is why accelerating the transition to a circular and smart agri-food economy is no longer just a strategic choice but a systemic necessity.

**Conclusions**

The study highlights the strategic importance of integrating emerging technologies into agri-food chains to facilitate the transition to a circular economy. Research results demonstrate that the use of digital solutions, such as the Internet of Things, blockchain, artificial intelligence, and biotechnologies, directly contributes to reducing waste, optimising resources, and increasing transparency in the food supply chain. It also highlighted that technologies can act as a multiplier for economic, social and environmental sustainability, mainly when supported by coherent public policies and targeted investments.

At the same time, research has highlighted several systemic barriers that limit the widespread application of emerging technologies, including high costs, lack of digital infrastructure, skills shortages and regulatory issues. Identifying solutions that exclude the above-mentioned barriersis is a prerequisite for scaling up technological impact in the agri-food sector.

From the perspective of future research, an in-depth investigation into the economic efficiency of each emerging technology using quantitative methods is necessary in different regional contexts. At the same time, a comparative analysis of the implementation models in various EU countries is necessary to identify good practices that can be adapted for countries in the process of development and European economic integration, such as the Republic of Moldova. Of significant interest is also the study of the interactions between value chain actors in decentralised digital environments, as well as the social impact of automation in rural communities. These research directions can strengthen the evidence base necessary to develop integrated and tailored policies that accelerate the adoption of technological circularity in agri-food systems at both European and national levels.

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