# VALUE CHAINS AND INNOVATION ECOSYSTEMS: HOW DIGITALIZATION SHAPES COMPETITIVENESS AND SUSTAINABILITY IN THE WOOD-PROCESSING SECTOR

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***Abstract***

*The growing pressure for sustainability, decarbonization, and digitalization is reshaping how Slovak enterprises in the wood-processing industry build competitiveness. The paper examines how digital technologies, sustainable innovations, and value chains drive the transition toward a circular and climate-neutral economy. It focuses on Smart Industry, the Internet of Things (IoT), and Artificial Intelligence (AI), which enhance resource efficiency, reduce environmental impact, and enable transparent supply-chain management. Emphasis is placed on innovation ecosystems—cooperation among firms, start-ups, and regional actors—in applying ESG principles. The findings underline the need for digitally driven and sustainability-oriented supplier–customer integration that generates synergies within smart, green regions of Slovakia, while noting barriers such as low investment in green innovation, limited technological readiness, and insufficient green skills. Positive examples, such as the SmartHead platform, show that linking technology with sustainability enables transparent ESG reporting, builds trust, and creates value for people, the planet, and business.*

***Key words:***
*sustainability, value chains, digitalization, green innovation*

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## INTRODUCTION

The growing convergence of sustainability, digitalization, and climate neutrality represents a defining transformation of European industry, often described as the "twin transition" (Elavarasan et al., 2022). Within this dynamic context, Slovakia's wood-processing sector occupies a strategic position as a pillar of the national bioeconomy and regional development, contributing significantly to employment, value creation, and the circular use of renewable resources (Kristakova et al., 2021; Paluš et al., 2020). Increasing regulatory and societal pressures, driven by the European Green Deal and climate-neutrality objectives, have accelerated the demand for sustainable innovation and green transformation in resource-intensive industries (Carmona-Martínez et al., 2024; Sikora, 2020).

Digitalization—encompassing Smart Industry, IoT, and Artificial Intelligence—has emerged as a key enabler of this transformation, improving energy efficiency, transparency, and traceability across value chains (Ferreira et al., 2023). However, its diffusion remains uneven among Slovak enterprises due to high investment costs, skill shortages, and limited technological readiness (Maksymova & Nastase, 2024). Integrating digital and sustainable practices across the entire value chain is therefore essential for strengthening competitiveness and fostering regional innovation ecosystems that align with ESG principles (Stroumpoulis & Kopanaki, 2022).

Against this background, the present study investigates how digital technologies, sustainable innovations, and value-chain integration jointly enhance the competitiveness and climate performance of Slovak wood-processing enterprises. It contributes to the discourse on circular and climate-neutral economies by identifying both enabling mechanisms and structural barriers that shape the sector's twin transition.

## 2. PROBLEM FORMULATION AND METHODOLOGY

### *2.1 Problem Formulation*

The accelerating convergence of sustainability imperatives, digital transformation, and innovation ecosystems is reshaping the competitive landscape of the Slovak wood-processing industry. This sector, a strategic pillar of the national bioeconomy, has become a testbed for implementing the European Union's "twin transition" — the simultaneous shift toward digitalization and climate neutrality (Elavarasan et al., 2022; Kristakova et al., 2021;). The integration of environmental, social, and governance (ESG) principles into industrial value chains reflects an emerging paradigm in which economic efficiency, ecological responsibility, and technological sophistication reinforce one another (Sikora, 2020).

Digital technologies are key enablers of this transformation. Tools such as artificial intelligence (AI), the Internet of Things (IoT), and cyber-physical systems (CPS) enhance transparency, optimize material flows, and facilitate predictive maintenance in manufacturing (Singh et al., 2022). In wood-processing enterprises, the use of smart sensors, digital twins, and blockchain-based traceability systems supports real-time resource monitoring, thereby reducing waste and carbon emissions while improving process efficiency (Liu et al., 2023). These technologies also foster new business models, including servitization and digital platforms, which strengthen the integration of suppliers, producers, and customers along sustainable value chains (Stroumpoulis et al., 2024).

The role of innovation ecosystems in this context is pivotal. The wood-processing industry increasingly depends on networks of enterprises, start-ups, and research institutions that co-create technological and ecological value (Vostriakova et al., 2023). Such ecosystems promote open innovation, cross-sectoral collaboration, and the exchange of green knowledge, leading to the diffusion of advanced materials such as bio-based composites and non-wood biomaterials (Antov et al., 2023). These developments illustrate the systemic shift toward circularity — where value creation is decoupled from resource depletion through recycling, reuse, and renewable feedstocks (Osvaldová & Potkány, 2024; Huber et al., 2023).

At the macroeconomic level, this transformation aligns with the European Green Deal's objectives for climate neutrality by 2050, demanding decarbonization across all industrial sectors (Carmona-Martínez et al., 2024). However, barriers such as low investment in green innovation, limited digital readiness, and insufficient green skills persist, particularly among small and medium-sized enterprises (Maksymova & Nastase, 2024; Chatzistamoulou, 2023). In Slovakia, regional disparities and structural weaknesses may hinder the diffusion of digital and sustainable technologies. Nonetheless, successful examples—such as the SmartHead platform integrating ESG data management—demonstrate that combining transparency with technology enhances trust, stakeholder engagement, and long-term competitiveness (Šulyová et al., 2020).

Thus, the theoretical foundations of this study rest upon three interlinked pillars: 1. the digital transformation of production systems through Smart Industry and IoT, 2. the sustainability transition driven by ESG and circular economy principles, and 3. the formation of innovation ecosystems that mediate these processes within regional and national value chains. Together, these dimensions form a comprehensive framework for understanding how Slovak wood-processing enterprises can leverage digital and sustainable innovation to achieve competitiveness in a climate-neutral economy (Paluš et al., 2020; Stroumpoulis et al., 2024).

### *2.1 Research Aim and Questions*

The primary aim of this research is to analyze the interrelationship between digitalization, innovation, and ESG (Environmental, Social, and Governance) performance in the Slovak wood-processing industry, with a particular focus on how digital technologies and innovation ecosystems support the transition towards a circular and climate-neutral bioeconomy. The study seeks to identify how tools such as IoT, AI, and data-driven management enhance operational efficiency, transparency, and environmental sustainability while simultaneously strengthening governance

and stakeholder engagement along value chains. Furthermore, it aims to examine the barriers and enabling factors influencing the adoption of ESG-oriented digital transformation and to propose recommendations for building innovation ecosystems that integrate economic competitiveness with sustainable and responsible business practices.

Research Questions:

1. How does digital transformation enhance ESG (Environmental, Social, and Governance) performance in the Slovak wood processing industry?
2. What role do innovation ecosystems and digital technologies (IoT, AI, data analytics) play in promoting sustainability, transparency, and competitiveness along the wood value chain?
3. What key barriers and enabling factors influence the integration of digitalization, innovation, and ESG principles in Slovak wood-processing enterprises?

### *2.3 Methodology*

The study employs a qualitative secondary analysis, exploratory research design aimed at understanding how Slovak wood-processing enterprises integrate digital technologies, sustainable innovations, and value-chain collaboration in pursuit of competitiveness and climate neutrality. The empirical analysis is based on secondary data collected from peer-reviewed academic literature, national strategic documents, and corporate case evidence (e.g., SmartHead, Bučina DDD).

A thematic content analysis approach was applied to identify patterns and relationships among digital transformation, ESG implementation, and innovation ecosystems. Themes were developed inductively from data and validated through iterative comparison across sources. Triangulation of information from academic, policy, and industry perspectives ensured analytical rigor and credibility.

Data interpretation followed an ESG-based competitiveness framework, which integrates environmental performance (resource efficiency and carbon reduction), social performance (stakeholder trust and employee skills), and governance performance (transparency, reporting, and innovation management). This approach allows for a multidimensional understanding of how digital transformation contributes to sustainable competitiveness within the Slovak wood-processing industry.

## 3. PRACTICAL PART: DIGITALIZATION, INNOVATION, AND ESG IN THE SLOVAK WOOD PROCESSING INDUSTRY

The growing interdependence of digitalization, innovation, and sustainability is profoundly transforming the Slovak wood processing industry. In recent years, a new paradigm has emerged in which digital transformation and green innovation act as key drivers of improved ESG (Environmental, Social, and Governance) performance, resource efficiency, and long-term competitiveness. Empirical research from the last decade confirms that the integration of digital technologies, ecological solutions, and value-chain collaboration represents a critical mechanism for enhancing both environmental and economic performance (Loučanová et al., 2020; Su et al., 2023; Feng & Nie, 2024; Sang et al., 2025).

### *3.1 Innovation Orientation and ESG Integration in Slovak Enterprises*

According to Loučanová et al. (2017), innovations in Slovak wood-processing enterprises are primarily oriented toward modernization of production technologies and optimization of raw material processing to improve efficiency and product quality. Larger enterprises increasingly invest in digital transformation, while small and medium-sized enterprises (SMEs) focus mainly on incremental innovations driven by regulatory compliance.

A later study by Loučanová et al. (2020) revealed that experts and entrepreneurs in the sector prioritize environmental and process innovations, such as material efficiency, waste recycling, and low-emission production processes. These directions align with the principles of the circular economy and the ESG framework, in which digital tools support transparency, accountability, and environmental monitoring (Chen & Wang, 2024; Yang et al., 2023). However, innovation strategies in practice

often remain narrowly technological, lacking a holistic ESG integration that connects innovation with social responsibility, governance quality, and long-term sustainability goals.

The main obstacles to this alignment include financial constraints, low digital maturity, and insufficient green skills, which limit the sector's capacity to implement comprehensive ESG-oriented innovations (Melichová et al., 2021; Maksymova & Nastase, 2024).

### *3.2 IoT, Supply Chains, and ESG Transparency*

A significant shift towards digitalization has been documented by Šulyová and Koman (2020), who analyzed the adoption of Internet of Things (IoT) technologies in logistics within Slovak wood-processing enterprises. Their findings demonstrate that IoT implementation can reduce operational costs by up to 20%, improve supply-chain traceability, and enable real-time data analytics—a foundation for stronger governance and ESG reporting.

Compared to global leaders such as West Fraser Timber (Canada) or Weyerhaeuser (USA), Slovak enterprises currently employ mostly basic IoT applications—moisture sensors, RFID tagging of raw material, and GPS-based transport monitoring. International best practices, however, indicate that integrating IoT with blockchain and cloud-based systems achieves full supply-chain transparency, enabling immutable audit trails and green logistics certification (Wei & Zheng, 2024; Yu et al., 2024).

Šulyová and Koman (2020) proposed a three-phase logistics audit model to guide digital transformation:

1. Descriptive phase – collection of process data;
2. Diagnostic phase – identification of inefficiencies and bottlenecks;
3. Recommendation phase – formulation of IoT-based improvement strategies.

Such audits support the implementation of Industry 4.0 principles by integrating AI-driven decision support, automated guided vehicles (AGV), augmented reality (AR) scanning, and digital twins for predictive maintenance. These technologies jointly enhance energy efficiency, occupational safety, and ESG governance, providing verifiable data for sustainability reporting.

### *3.3 Artificial Intelligence and Green Innovation in Wood Processing*

Recent advances in artificial intelligence (AI) further illustrate how digitalization supports ESG outcomes. Vacek et al. (2024) applied AI for defect detection in roundwood using CT scanning, leveraging 3D scanning and neural networks to identify wood species, knots, and pith with over 95% accuracy. This data-driven optimization minimizes waste, reduces energy intensity, and contributes directly to climate neutrality and environmental efficiency, reinforcing the *Environmental* dimension of ESG.

From the *Governance* perspective, AI enhances internal control and data-driven decision-making, thereby improving transparency and accountability. Such technologies exemplify how green innovation and digital capability building serve as mediating mechanisms between digital transformation and ESG performance (Wu & Li, 2023; Wei & Zheng, 2024).

### *3.4 Bioinnovations, Value Chains, and Stakeholder Integration*

As Martínková et al. (2019) note, bio-based innovations—including bio-adhesives, biocomposites, and nanocellulose—create higher added value while supporting eco-efficiency. Integrating these innovations within digital value chains fosters a shift toward the circular bioeconomy, characterized by resource recirculation, renewable inputs, and reduced environmental impact.

In this context, digital stakeholder integration has emerged as a critical governance instrument. Real-time data exchange between suppliers and customers enhances trust, transparency, and ESG disclosure (Mohiuddin et al., 2024). Empirical evidence from Central Europe confirms that joint transport planning and logistics optimization can reduce procurement costs by 24–40% (Kogler et al., 2021), while simultaneously contributing to social and environmental performance.

Table 1: ESG-oriented digital strategies for sustainable logistics and supply chain integration.

| Strategy | ESG Impact | Effect / Benefit | Source |
|---|---|---|---|
| **Joint transport planning** | E, G | Reduced logistics emissions and costs (up to 24%) | Kogler et al. (2021) |
| **Higher transport utilization** | E | Fuel savings up to 40% | Kogler et al. (2021) |
| **IoT-enabled logistics** | E, G | 20% cost reduction; real-time traceability | Šulyová & Koman (2020); Yu et al. (2024) |
| **Real-time data sharing** | S, G | Improved collaboration and transparency | Mohiuddin et al. (2024) |

Source: Kogler et al. (2021); Šulyová & Koman (2020); Yu et al. (2024) ; Mohiuddin et al. (2024)

Digitalization thus functions as a multi-dimensional ESG enabler: improving operational efficiency (*Governance*), reducing environmental impact (*Environment*), and strengthening collaboration and social responsibility (*Social*). The convergence of digital and sustainable processes generates a synergistic ESG effect, supporting Slovakia's transition to a climate-neutral bioeconomy.

### *3.5 Barriers, Recommendations, and Innovation Ecosystems*

Despite visible progress, the digital-ESG transformation of the Slovak wood processing sector faces structural barriers: high investment costs, limited financing, insufficient coordination between research and industry, and an underdeveloped ecosystem for ESG-driven innovation (Loučanová et al., 2020; Melichová et al., 2021).

Table 2: Typology of Barriers

| Type of Barrier | ESG Dimension Affected | Description | Sources |
|---|---|---|---|
| **Financial** | E, G | Insufficient capital for green and digital transformation in SMEs | Loučanová et al. (2017); Melichová et al. (2021) |
| **Informationa** | G | Weak awareness of innovation and ESG funding opportunities | Štěrbová et al. (2016) |
| **Managerial** | G | Lack of coordination between innovation and ESG policies | Beckmann et al. (2020) |
| **Market** | S, G | Low competitiveness against innovative foreign producers | Kaputa et al. (2015) |
| **Skills-related** | S | Deficiency in digital and green skills | Maksymova & Nastase (2024); Chatzistamoulou (2023) |

Source: Loučanová et al. (2017); Melichová et al. (2021) ); Štěrbová et al. (2016) ); Beckmann et al. (2020); Kaputa et al. (2015) ); Maksymova & Nastase (2024); Chatzistamoulou (2023)

## 4. DISCUSSION

The study confirms that digitalization and sustainability form a mutually reinforcing foundation of competitiveness in the Slovak wood-processing industry, consistent with international findings (Su et al., 2023; Chen & Wang, 2024; Wei & Zheng, 2024). Similar to observations by Konovalova and Burtsev (2024), a digital divide persists between larger enterprises and SMEs: while leading firms invest in smart technologies and ESG reporting, smaller ones remain in the early stages of transformation. This gap limits the diffusion of green innovation, reduces transparency, and slows progress toward circular and climate-neutral objectives.

Our findings align with Zhang et al. (2022) and Kumar et al. (2022), who emphasize that limited financing, low technological readiness, and weak cooperation with research institutions are primary barriers for SMEs. In Slovakia, these constraints are further reinforced by regional disparities and skill shortages, confirming that the twin transition requires not only capital investment but also systemic capacity building and governance reform.

At the same time, the Slovak experience mirrors global evidence that digitalization and innovation enhance ESG performance through improved efficiency, resource allocation, and stakeholder transparency (Wu & Li, 2023; Yang et al., 2023). As in other manufacturing sectors, the Slovak wood industry demonstrates that the integration of AI, IoT, and data analytics directly supports the Environmental and Governance dimensions of ESG by enabling real-time monitoring and data-driven decision-making.

However, the current innovation ecosystem in Slovakia remains fragmented. Compared with best practices in Western Europe and Asia (Li et al., 2025; Yu et al., 2024), cooperation between enterprises, research institutions, and start-ups is still limited. This weakens the diffusion of bio-based innovations, such as composites and nanocellulose, and delays the transition to a circular bioeconomy (Osvaldová & Potkány, 2024; Beckmann et al., 2020).

In this regard, our observations correspond with recent studies on the circular and climate-neutral economy in Slovakia (Paluš et al., 2020; Kristakova et al., 2021; Korneliuk, 2024), which stress that despite high potential for sustainable growth, the sector faces barriers in governance, financing, and innovation diffusion. Addressing these will require strengthening regional innovation ecosystems, developing green and digital skills, and fostering cross-sectoral cooperation to balance efficiency, biodiversity, and climate goals.

In summary, the Slovak wood-processing industry reflects broader international trends: while digitalization and innovation clearly improve ESG performance and competitiveness, progress remains uneven. Bridging the digital divide—especially for SMEs—and linking technology with sustainability through collaborative innovation ecosystems are essential steps toward a resilient, circular, and climate-neutral bioeconomy.

## CONCLUSION

Digitalization, sustainability, and innovation ecosystems have become key drivers of competitiveness in the Slovak wood-processing industry. The ongoing twin transition—linking digital and green transformation—enhances efficiency, transparency, and ESG performance across value chains. Technologies such as IoT and AI improve resource use, reduce emissions, and strengthen governance through data-driven decision-making and reporting.

Despite progress, barriers remain: high investment costs, low digital maturity, and a lack of green skills limit the sector's transformation, especially among SMEs. To overcome these challenges, stronger cooperation between business, government, and academia is essential. Targeted investment support, skill development, and innovation networks can accelerate digital and sustainable change.

In sum, connecting technology with sustainability turns traditional wood value chains into smart, transparent, and climate-responsible ecosystems. Such integration not only boosts competitiveness but also creates long-term value for people, the planet, and business.

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