

Received: 07 Oct. 2025; Revised: 08 Nov. 2025; Accepted: 26 Jan. 2026
<https://doi.org/10.22306/al.v13i2.774>

Specification of employee competencies in creating green innovations as part of the enterprise's technological foresight

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Keywords: green innovations, technological foresight, competencies.

Abstract: This article maps the interconnections between (i) determinants of green innovation implementation, (ii) employee competencies, and (iii) Industry 4.0/5.0 digital technologies. A systematic literature review of the Scopus and Web of Science databases (2019–2025) according to the PRISMA protocol identified 23 relevant studies; 15 of these were analysed using open and axial coding. The output consists of five external determinants (K1–K5), a three-level competency framework (strategic, organizational, individual), and five digital themes (D1–D5). The results show that the synergy of stakeholder pressure and green financing (K1+K4) is the primary driver of innovation. Quick wins (green motivation, internal communication) create a cultural foundation, while data analytics and eco-design are strategic accelerators. The transformation is driven by cyber-physical systems and human-centric I5.0, but requires high capital investment and reverse logistics. We propose a three-stage development framework: (1) modular micro-credential programs for digital and environmental skills, (2) mentoring and job rotation for the transfer of tacit knowledge, and (3) a foresight lab that combines scenario workshops with strategic competency training. The study provides the concept of the "Digital-Sustainability Nexus," which explains how digital technologies simultaneously accelerate and facilitate green innovation and which competencies are key to this process. The results offer managers a practical roadmap of development, research, and policy priorities on the path to a carbon-neutral industry.

1 Introduction

Today, enterprises are facing a dual transformation: environmental and digital. On the one hand, there is growing pressure from governments and stakeholders for manufacturing to reduce its carbon footprint; on the other hand, the deployment of Industry 4.0/5.0 technologies is accelerating, transforming the way work is organized. Green innovation is therefore no longer merely a technical matter of investment, but above all a question of human capital – i.e., the ability of employees to understand, design, develop and operate solutions that combine sustainability with digital efficiency. If the competence base lags behind, investment in green technologies stagnates or fails; if, on the other hand, it is rebuilt in line with new requirements, it becomes a multiplier of value and a key differentiator for the company.

In response to this challenge, the relevant literature increasingly highlights the need to upskill employees' competencies – from production line operators to strategic management – so that they can simultaneously address environmental goals, digital processes, and economic efficiency. The following passage breaks down these skills into four interconnected areas that repeatedly emerge in empirical studies [1,2] as key building blocks of green transformation. A review of the literature shows that competencies naturally cluster along two axes: **Functional dimension** – ranging from strictly technical skills to creative-innovative and environmental knowledge; **Systemic level** – spanning from the individual employee to the team/organizational level to the strategic level of the enterprise.

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At their intersection, four domains emerge that cover the entire "life cycle" of green innovation – from idea to circular closure of material loops. This structure (Chapter 2.1) also allows for a logical follow-up to the methodological analysis of competencies in Section 2.3 (Significance for Small and Medium-Sized Enterprises).

2 Literature review

2.1 *Employee competencies for green innovation*

The development of green production and innovation in enterprises is inseparably linked to the formation of a new type of workforce. Employee competencies must be transformed to meet the challenges of environmental sustainability, digital transformation, and the principles of the circular economy [1,2].

Technical skills

Employees must have technical skills that allow them to implement environmentally friendly technologies, optimize energy and material efficiency, and apply circular economy principles [2]. Technical skills and abilities include, for example, knowledge of digital tools to support circular strategies, the ability to design products with a life cycle that takes recycling and renewal into account, and mastery of reverse logistics processes [1].

The implementation of technologies to reduce energy intensity, as well as knowledge of cleaner production, play a key role, with an increased ability of workers to reconfigure manufacturing processes to improve environmental compliance and reduce waste being emphasized [3]. Technical skills and abilities also include the development of skills related to the collection and processing of environmental data, as well as the introduction of green technologies into the production environment [4].

Innovative skills

Creative and systemic thinking are crucial for the development of green innovation. Innovative skills enable employees to identify new environmental solutions, adapt to rapidly changing technologies, and actively contribute to innovation teams. The importance of green creativity is emphasized, where employees propose new environmental solutions, revise existing processes, and promote the development of sustainable ideas [5].

The ability to be involved in environmentally friendly innovation processes plays an important role in the so-called green dynamic abilities of enterprises, which enable them to respond quickly to environmental challenges through innovation. This implies the need to develop flexibility, teamwork, digital literacy, and agility in the face of changes [1,6].

Artificial intelligence (AI) currently has an important role to play, significantly shaping green innovation through automation, digitalisation and intelligent data processing. AI enables employees to effectively analyze big environmental data, to identify inefficient processes, and to optimize resource use. Thus, part of innovative competencies includes understanding and participating in the implementation AI tools in the development and assessment of environmental solutions [7]. Enterprises that also promote collaborative innovation cultures based on sustainability achieve higher levels of environmentally oriented business – which is only possible with a sufficiently competent and proactive workforce [4,8].

Knowledge of environmental protection

Green innovation cannot be realised without sufficient knowledge of environmental issues. Systematic environmental education of employees is one of the fundamental tools for enterprises to achieve environmental performance. Education should cover areas such as waste management, environmental legislation, sustainable design, and environmental metrics [1].

In terms of motivating employees to behave sustainably, it is important not only to provide formal education, but also to create a so-called psychological green climate and to support the value anchoring of environmental behavior [9]. Successful enterprises invest in the development of "environmentally oriented" leaders who have the ability to communicate sustainable goals and lead others to achieve them in everyday practice [4,10]. The basis for effective decision-making in the area of sustainability is the integration of environmental knowledge into corporate management and performance evaluation systems [1,11].

Multidisciplinary and interconnected competence base

In summary, green innovation requires a complex and multidisciplinary combination of technical, innovative, and environmental competencies. Modern enterprises should build "green talent capital" that combines digital skills with the principles of sustainability and the circular economy [1,12]. It is necessary for enterprises not only to identify strategic competencies, but also to develop them through targeted training, adaptation programs, and partnerships with the academic community, thereby increasing their ability to respond to sustainability challenges [1,13].

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2.2 Technological foresight as a tool for strategic planning of sustainable innovation

Technological foresight is a systematic approach to predicting future development trends and their potential impact on the world of business. At its core is the ability to anticipate which technologies will be strategically important for developing sustainable innovations. Foresight supported by digital transformation enables enterprises to manage information complexity and reduce uncertainties associated with environmental and social requirements [14]. The introduction of technological foresight into strategic planning increases the ability of enterprises to adapt to changing conditions and take advantage of new opportunities. The concept of "twin transition," which combines digital and green transformation, highlights the need for synergistic development of technologies and environmental approaches. The combination of digital technologies and circular economy principles forms the basis for modern strategic decision-making [2].

In terms of building foresight capacities, it is important to understand foresight as a dynamic ability that combines internal technological prerequisites with external market and environmental signals. Especially in the case of technology-oriented enterprises, it appears that the ability to anticipate technological trends and evolving regulatory frameworks is closely linked to their ability to link technological readiness with expected market response [15]. The ability to predict and respond quickly becomes a competitive advantage in this context, with an emphasis also on so-called "learning organizations" that use feedback from foresight exercises for continuous strategic adjustments [16]. An equally important aspect is the integration of foresight into open innovation practices, in which enterprises connect internal knowledge with external partners. This increases the likelihood of success in developing new products and services that reflect future environmental challenges [16].

In the context of anticipatory decision-making, predictive models are often supported by artificial intelligence and real-time analytics, enabling active and flexible decision-making in under conditions of uncertainty [17]. Current research also indicates that foresight processes are not isolated activities, but take place within broader collaborative ecosystems that emphasize the importance of participation not only by internal employees, but also by customers, academia, and technology partners. This participatory dimension strengthens the ability of enterprises to adapt to complex systemic changes and to more effectively anticipate emerging technologies before their widespread adoption in the market [18].

The effective implementation of foresight depends on the active involvement of employees at all levels. It is important to foster a culture of participation and involve employees in formal and informal foresight activities, such as workshops, feedback sessions, and discussion forums focused on environmental challenges [1]. Employees are carriers of knowledge that can be systematically used through foresight processes to anticipate technological changes. Employees with a high degree of so-called "technological sensitivity" can contribute to the early identification of technological trends that can positively influence the environmental performance of an enterprise [14,19].

Anticipating technological change requires specific tools and skills. Digital capabilities are crucial, enabling enterprises to collect and analyze data to identify new technological opportunities. In this context, foresight is a tool that allows risks and the identification of risks and opportunities and the planning of product and process adaptation [14,20]. One of the practical outputs of foresight is the identification of emerging technologies with potential for green innovation. Such technologies include artificial intelligence, which, through so-called digital financing, provides new opportunities for funding green projects, especially in areas with lower environmental quality and high environmental demands. AI is thus becoming not only a predictive tool, but also an active means of transforming enterprise innovation toward sustainability [7]. These forecasts form the basis for the creation of long-term innovation strategies that take into account the need to reduce emissions, conserve resources, and close material flows [11,14].

Technological foresight has a crucial role in linking the Industry 4.0 paradigm and the emerging Industry 5.0 concept with sustainability principles. Foresight processes make it possible to identify specific technologies that not only enhance efficiency but also reduce the environmental impact of production, such as autonomous manufacturing systems, robotics, and green digital twins [14]. Employees participating in these transformations must be prepared to cope with changes in technology while understanding their environmental implications. Therefore, foresight is not only a management tool but also a challenge for HR departments and education systems [8].

Modern foresight is a process of continuous feedback based on participation and shared knowledge. Enterprises that create innovative ecosystems with the active participation of employees, customers, academia, and technology partners are able to anticipate technological changes more effectively and respond to them innovatively [6,14]. The importance of so-called open foresight, which is based on external partnerships and the active search for external knowledge, is also highlighted. This approach strengthens the ability of enterprises to identify green technology trends before they become widespread [14,21].

It is important to emphasize that foresight is a long-term process requiring continuous learning and adaptation. Enterprises must systematically develop organizational learning focused on the ability to anticipate future challenges and create innovative responses with environmental impact [12,14]. From the same perspective, they highlight the importance of strategic foresight in enterprise planning, emphasizing the need to connect technological knowledge with future visions. In their view, foresight is not only a tool but also a way of thinking that enables enterprises to remain competitive in times of growing environmental challenges [13,14].

2.3 *The concept of green innovation and its importance for enterprises in the context of sustainability*

Green innovations (eco-innovations) represent a form of technological or non-technological progress aimed at reducing negative environmental impacts while maintaining or enhancing enterprise performance. These innovations that reduce environmental risk, pollution, and resource consumption throughout their life cycle compared to alternatives [8]. Green innovations can take the form of product, process, organizational, or marketing changes. They encompass solutions that enable more efficient use of resources, reduction of material costs, waste recycling, or the design of environmentally friendly products [11].

The main benefit of green innovation is its ability to harmonize economic and environmental interests. Green technologies, such as solar and wind energy, contribute to reducing emissions, increasing energy efficiency, and creating new workplaces, thereby strengthening economic growth and environmental quality [6]. At the same time, green innovation provides enterprises with an opportunity to enhance their reputation and gain a competitive advantage. The environmental performance of enterprises supported by green innovation has a positive impact on customer perception of the brand, which has a direct impact on business success [22].

Forms and types of green innovations

Green innovations develop in two forms – incremental and radical. The former bring gradual improvements in environmental efficiency, while the latter represent fundamental technological transformations. The importance of digital technologies and their combination with environmental goals is highlighted, giving rise to so-called digital green innovations – for example, the implementation of smart sensors to monitor resource consumption [14]. In the context of Industry 4.0, the ability to create interconnected systems that reduce environmental impacts through automation and AI is becoming increasingly important. Green technologies such as smart manufacturing and green computing are becoming an integral part of enterprise innovation [12].

Despite the positive potential of green innovation, enterprises face several barriers, such as high initial investment costs, regulatory uncertainty, and low environmental literacy among employees. To successfully overcome these barriers, it is necessary to invest in education, competence development, and partnerships within innovation ecosystems [2]. Another specific prerequisite for success is the development of skills in digital finance, which – supported by AI technologies – opens up new forms of financing for green innovation. Digital finance, including tools such as crowdfunding, electronic commercial papers, and smart contracts, enables flexible and transparent capital allocation while reducing information asymmetry between enterprises and investors [7].

Organizational culture focused on sustainability and supporting open innovation also plays a key role. Enterprises with a stronger green culture achieve a higher level of environmental innovation implementation, particularly in the areas of product design and sustainable packaging [5,11].

Importance for small and medium-sized enterprises

Green innovation plays a specific role in the small and medium-sized enterprise (SME) segment, which accounts for more than 90% of all enterprises. Although SMEs often face resource constraints, their flexibility allows them to implement green measures more rapidly and transform their business models towards sustainability [3,11]. The regional and sectoral context is also significant. Enterprises participating in local green clusters achieve higher environmental performance due to synergies between enterprises, the public sector, and research institutions [4,11].

Green innovations are a key tool for enterprises to achieve environmental goals while creating a competitive advantage. Their importance is growing in the context of climate challenges, regulations, and social pressure. Enterprises need to integrate the principles of green innovation into their long-term strategies, with the active involvement of employees, digital support for processes, and cooperation with the external environment being key [11,13].

3 Methodology

This section of the article describes the process through which the key prerequisites for the successful implementation of green innovations in enterprise practice were identified, synthesized, and interpreted. It combines a systematic literature review, thematic meta-synthesis, and cross-analysis to integrate three complementary perspectives:

1. **Determinants and conditions for implementation of green innovations in enterprises** (Table 1);
2. **Competency requirements for employees who implement these innovations** (Table 2);
3. **Synergetic links between green innovations and Industry 4.0 / 5.0 digital paradigms** (Table 3).

These three areas were chosen because the literature suggests that the interconnection of enterprise determinants, human capital, and digital technologies that forms the core of the so-called twin transition – the parallel green and digital transformation of industry.

First, the Scopus and Web of Science databases (2019-2025) were systematically reviewed following PRISMA principles, using a combination of the keywords *green innovation*, *sustainable technology adoption*, *competence*, and

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Industry 4.0 / 5.0. After duplicates were removed and inclusion criteria were applied (peer-reviewed articles, direct relevance to the topic), 23 relevant publications were identified. From these, those providing empirical data on one of the three areas mentioned above were selected for deeper analysis; the results are presented in three synthetic tables directly in the text.

At the analytical level, **open coding** was applied, followed by **axial coding** and **triangulation** across the individual datasets. This approach allowed the creation of a **conceptual framework**, which will be connected at the end of the chapter to recommendations for the development of employee competencies and for strategic planning of future technologies.

3.1 Conditions for the implementation of green innovations

First, empirical studies from the period 2019–2025 were systematically searched (Scopus and Web of Science, keywords: *green innovation, sustainability drivers, technology adoption, Industry 4.0 / 5.0*). After removing duplicates and applying inclusion criteria (peer review, direct relation to the conditions for implementation of green innovations), five relevant papers remained. From each, we extracted:

1. Bibliographic data (author, year).
2. Main type of determinants (authors' own wording).
3. Specific findings (quantitative or qualitative summaries).

Thematic coding of determinants

Open coding → axial coding was used for the synthesis; five super-categories were identified, which will be linked to competencies and digital technologies in the subsequent sections.

3.2 Employee competencies needed to implement green innovations

In the second step, a systematic analysis focused on empirical studies that explicitly quantify or qualitatively describe the employee competencies necessary for the developing green innovations. Five relevant studies were identified from the Scopus and Web of Science databases (2019–2025) (Table 2). Each study was coded according to a three-level framework (strategic – organizational – individual level), and the competencies were subsequently assigned to determinants K1–K5, as derived in subsection 3.1.

Thematic open coding, followed by secondary axial coding, was methodically applied to capture the relationships between specific competencies and business – ecosystem conditions. In the final phase, a conceptual importance × difficulty matrix (criteria: frequency of occurrence, declared benefit, implementation barriers) was constructed, forming the basis for the discussion on development programs (Chapter - Conclusion).

3.3 Linking green innovation and the Industry 4.0 / 5.0 paradigm

The third phase of the systematic review focused on studies analyzing synergies between Industry 4.0/5.0 digital paradigms and green innovations. Six relevant publications (2019–2025) were identified that met the criteria: (i) peer-reviewed article, (ii) explicit link between I4.0/5.0 → environmental performance, (iii) methodological transparency.

Three variables were extracted:

1. Bibliographic data (Article).
2. Type of determinants – key attributes of the digital paradigm.
3. Findings – how digital tools support green innovation.

4 Results and discussion

This chapter summarizes the results of the three-phase analysis. First, external determinants that drive or hinder green innovations are presented, followed by a summary of the employee competency profile and a discussion of how Industry 4.0 / 5.0 digital technologies amplify these factors.

4.1 Conditions for the implementation of green innovations

Systematic research revealed five key determinants (K1–K5) that are repeatedly associated with the successful implementation of environmental solutions in empirical studies. These range from stakeholder and regulatory pressure to macroeconomic conditions. Their specific form and quantified impacts are summarized in the following table.

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Table 1 Determinants of green innovation adoption – synthesis of empirical findings (2019-2025) (own processing, 2025)

Article (author, year)	Type of determinants	Specific findings
Baah et al. (2021)	Stakeholder pressure, regulatory and organizational factors	Organizational pressure: customers, employees, and suppliers; regulatory requirements increase the likelihood of adopting green innovations – GIs.
Block et al. (2025)	Innovation systems, intellectual property rights – IPR, policy	<i>Green patents</i> versus <i>green trademarks</i> : patents correlate better with emissions reductions; support from innovation clusters accelerates diffusion.
Haleem et al. (2023)	System requirements, technological and organizational capabilities	The 5R strategic tools (repair – reuse – remanufacture – recycle – recover) require integrated IT systems and standardized processes.
Hanif & Zheng (2025)	Green finance, renewable energy, regulatory tools	Green credit: A 1% increase in green financing leads to a 0.4% increase in the number of GIs; regulatory reliefs strengthens the effect by 20%.
Javed et al. (2025)	Technological, financial, and macroeconomic conditions	Investments in renewable energy sources and digitization (AI-managed networks) reduce emissions by 15%; with proper financial infrastructure, the transition is carried out more efficiently.

In the following text, abbreviations K1-K5 will be used for clear cross-links to competencies (section 3.2) and digital technologies I4.0/5.0 (section 3.3).

Table 2 Determinants of green innovation implementation (own processing, 2025)

Code	Category name	Description of typical determinants
K1	Stakeholder-regulatory	customer pressure, employee demands, government directives
K2	Technological and organizational readiness	state of infrastructure, ability to integrate new processes
K3	Intellectual property and innovation systems	patents, trademarks, ecosystem of collaboration
K4	Green financing and energy infrastructure	green loans, renewable energy sources
K5	Macroeconomic and financial factors	taxes, subsidies, energy price fluctuations

Key findings

Based on a comparative analysis of the five most relevant empirical studies, three key conclusions can be drawn:

- The synergy between customer pressure (K1) and the availability of green financial instruments (K4) is the dominant driver of green transformation.** All analyzed studies confirm that enterprises which simultaneously face strong stakeholder demand for sustainability and have access to preferential loans or tax incentives implement green innovations faster and on a larger scale.
- The technological readiness of an enterprise (K2) combined with effective intellectual property management (K3) becomes a critical factor, especially in the solution scaling phase.** When a prototype moves into mass production, the ability to integrate digital platforms (ERP, IoT, AI) while protecting know-how through patents or licensing models is crucial—otherwise, the benefits of innovation will quickly disappear in a competitive environment.
- Macroeconomic and political conditions (K5) determine the pace of diffusion, but are largely beyond the direct control of the enterprise.** Although enterprises can partially mitigate risks through hedging or diversification, the stability of regulations, energy prices, and monetary policy remains an external factor that ultimately determines the long-term return on green investments.

Together, these three findings show that a successful path to green innovation requires a holistic approach: strategic stakeholder and financial management must be linked to internal technological capacity and supported by a favorable macroeconomic environment.

4.2 Employee competencies needed to implement green innovations

The analysis of competencies is based on the five most relevant empirical studies and is organized within a three-level framework (strategic – organizational – individual).

The following table summarizes the competencies that the literature repeatedly identifies as key to the successful implementation of green innovations in the enterprises.

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Table 3 Competencies supporting green innovations (own processing, 2025)

Article	Types of competencies	Findings
Ahuja et al. (2019)	Human factors critical for sustainable production (HCSF)	13 competency factors were identified, divided into: Strategic – <i>green motivation, leadership, CRM, strategic alignment</i> ; Organizational – <i>communication, culture, teamwork, engagement</i> ; Individual – <i>green training, employee commitment, trust</i> . The most influential factors: green motivation, leadership, CRM; Recommendations: combination of training, systematic communication, and a participatory leadership style.
Kim et al. (2023)	Green work behavior – commitment, sharing knowledge, creativity	<i>Green HRM</i> – human resource management (GHRM) contributes to performance only when employees demonstrate: (i) green work engagement, (ii) active sharing of environmental knowledge, (iii) green creativity (mediator). A culture of feedback, recognition, and teamwork is crucial.
Marrucci et al. (2021)	Sustainable HR practices – recruitment, training, engagement, evaluation, remuneration	Different parts of GHRM have different effects on economic and environmental performance: hiring based on green values has an immediate impact; development (training) and rewards have a longer-term effect.
Straub et al. (2023)	General, sustainable, and circular skills for CBM – circular business models implementation	Taxonomy of 40 skills (six categories): innovative entrepreneurial skills, sustainable resource management, augmented reality and robotics, eco-design, reverse logistics, etc. Emphasis on soft skills: flexibility, critical thinking, lifelong learning, storytelling.
Trevisan et al. (2024)	Three categories – resilience, digital, specialized technical skills	A systematic research identified 40 competencies in three areas: (i) resilience skills (23), (ii) digital skills (7) – data analytics, VR/AR, robotics, (iii) technical skills (10) – eco-design, energy management, reverse logistics.

The synthetic grouping and links to determinants K1-K5 are shown in the following table.

Table 4 Synthetic grouping and linking to determinants K1-K5 (own processing, 2025)

Competency level	Dominant competencies	Link to determinants from Chapter 4.1
Strategic	<i>Green motivation</i> , green leadership, Customer-Relationship-Management sustainability oriented, strategic alignment of technologies	K1 (stakeholder-regulatory pressure): requires proactive leadership and CRM; K5 (macro-factors): need for strategic foresight and scenarios.
Organizational	Learning culture, internal communication, teamwork, participatory engagement	K2 (technological readiness): when implementing I4.0/5.0 digital tools, it is necessary to harmonize processes and culture; K3 (IPR and innovation systems): open innovation requires internal know-how sharing.
Individual	Lifelong learning, green technical skills (eco-design, energy engineering), data analytics, green creativity	K2 digital skills enable the use of IoT/AI to measure environmental performance; K4 (green finance) knowledge of green accounting and energy indicators determines access to financial incentives.

Matrix of significance × implementation difficulty (conceptual overview):

- „Quick wins“ (*high priority, low complexity*)

Green motivation and effective internal communication are the least capital-intensive, but have a disproportionately large impact on the success of green innovations. Enterprises can implement them immediately through short online training courses and motivational campaigns, thereby establishing a cultural foundation for further, more complex interventions.

- *Strategic accelerators* (*high priority, medium difficulty*)

Data analytics and eco-design require a mature I4.0 digital infrastructure and cross-functional teams, yet they bring measurable environmental and economic benefits. Investment in analytical platforms and collaborative eco-design workshops is therefore a logical next step after quick wins.

- *Transformational competencies* (*critical priority, high difficulty*)

Strategic alignment with the I5.0 paradigm and reverse logistics are the most capital- and process-intensive, but they determine long-term competitiveness in the circular economy. Their implementation requires high investments in automated reverse material flows, advanced robotics, and links to predictive demand models.

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Based on the above hierarchy of competency priorities and complexity, an implication framework was developed to translate the analytical findings into specific enterprise development mechanisms. An overview of this framework is provided in the following table:

Table 5 Implications for enterprise development programs (own processing, 2025)

Development mechanism	Purpose	Linking to competencies
Modular learning pathways (micro-credentials)	Flexibly combine digital (AI, Big Data) and environmental skills (LC-analysis, eco-design).	Support quick wins and prepares the ground for strategic accelerators.
Mentoring & job-rotation	Accelerate the transfer of tacit knowledge between R&D, production, and logistics; break down organizational "silo" effect.	Critical for adaptive data analytics and eco-design; reduces the risk of failure in I5.0 projects.
Integrated foresight-lab	Link long-term scenarios (K5) with practical competency training (K2 + K3) through workshops and digital simulations.	Creates a strategic framework for the transformation towards I5.0 and circular logistics.

Enterprises should proceed iteratively – first activating cultural and communication "quick wins," simultaneously developing data analytics and eco-design as strategic accelerators, and then, with the support of a foresight lab, investing in capital-intensive reverse logistics and human-centric I5.0 solutions. This minimizes the risk that large investments will outpace organizational readiness.

4.3 Linking green innovation and the Industry 4.0 / 5.0 paradigm

Digital transformation is reshaping the technical and organizational prerequisites for sustainability: cyber-physical systems, real-time data, and human-centric Industry 5.0 solutions are opening up new possibilities for circular flows and green business models. To assess how these technologies support eco-innovation, six recent empirical studies (2019-2025) were analyzed. Open and axial coding revealed five recurring digital themes (D1-D5) – ranging from cyber-physical integration to AI-supported foresight. Their content and key links to enterprise determinants and competencies are summarized in the following table.

Table 6 Digital determinants supporting green innovations (own processing, 2025)

Article	Types of determinants	Findings
Capatina et al. (2024)	Technological readiness, foresight approaches, AI integration	The study emphasizes that the ability to integrate cyber-physical systems (CPS) and artificial intelligence (AI) is key to the technical validation of green innovations in deep-tech start-ups.
Elias et al. (2025)	Technological readiness, foresight approaches, AI integration	The proposed framework combines AI and strategic foresight, thereby strengthening SMEs' resilience to regulatory pressure on sustainability.
Ghobakhloo et al. (2023)	Technological readiness, foresight approaches, value network	The identified "Industry 5.0 roadmap" describes 12 functions of digital manufacturing that reduce the environmental footprint and increase the adaptability of the value chain.
Lu et al. (2023)	Digital capabilities, strategic alignment of technologies, digital flexibility	Digital transformation through IoT and big data analytics improves circular material flows and minimizes waste streams in real time.
Mubarak et al. (2025)	Strategic foresight, knowledge management (exploration/exploitation), open innovation	Strategic foresight workshops and knowledge-sharing platforms accelerate the diffusion of green solutions across the supply chain.
Song et al. (2025)	AI integration, digital finance, technological support	AI-driven digital finance improves enterprises' access to green credit and accelerates the adoption of clean technologies.

Open and subsequent axial coding revealed five core themes (D1-D5) that overlap with previously identified determinants (K1-K5) and competency levels:

Table 7 Digital determinants (D1-D5) within the "Digital-Sustainability Nexus" – examples of technologies and main connection to enterprise competencies (own processing, 2025)

Code	Digital theme	Examples of technologies	Main connection
D1	Cyber-physical integration	CPS, digital twin, robotics	K2 increases technological readiness and requires individual technical skills (eco-design, robotics).
D2	Data-driven optimization	IoT, Big-Data, predictive analytics	Supports K4 access to green financing through transparent metrics; relies on digital competencies.

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D3	Artificial intelligence & machine learning	MLOps, generative AI	Accelerates the eco-innovation cycle, strengthens strategic leadership (adaptive scenarios in K5).
D4	Human-centric Industry 5.0	Collaborative robots, XR training	Increases employee acceptance; correlates with organizational competencies (learning culture, participation).
D5	Digital foresight & open innovation	Scenario platforms, crowdsourcing	Bridging K1 stakeholder pressure and strategic orientation requires strategic and organizational skills.

Conceptual framework „Digital-Sustainability Nexus“

By triangulating **environmental determinants (K1-K5)**, **competency levels**, and **digital tools (D1-D5)**, a **phase model** emerges: **Sensing** → **Seizing** → **Transforming**, which captures when and how digital technologies accelerate green innovation:

1. **Sensing** – IoT, Big Data, and AI algorithms (D2/D3) continuously monitor material and energy flows, convert them into KPIs (carbon footprint, water consumption), and send **real-time feedback** to stakeholders (K1). The result is immediate transparency, which increases pressure for sustainable decision-making.

2. **Seizing** – Digital foresight platforms and scenario simulations (D5) analyze the collected data, identify **specific investment windows** (e.g., the use of green credits or subsidies), and provide management with the basis for capital allocation. The success of this phase depends on **strategic green leadership** and the alignment of goals across the enterprise.

3. **Transforming** – Cyber-physical systems and human-centric I5.0 solutions (D1/D4) put selected projects into practice: they introduce circular flows, automate reverse logistics, and support collaborative robots. Implementation success depends on a **mature organizational culture** and the ability of employees to integrate digital and environmental skills.

The model clearly shows that digital technologies fulfill two roles simultaneously – first as an **accelerator** (shortening the time needed for data collection and analysis), and second as an **intermediary** (enabling the physical transformation of processes).

Impact and influence on practice and research

The next three perspectives – managerial, political-regulatory, and research – deliberately cover the entire decision-making chain of green transformation: the enterprise decides and invests, the regulator shapes the conditions, and research fills in the knowledge gaps needed for further progress:

- **Managerial contribution:** In enterprises that have integrated AI-driven foresight (combination of D3+D5), the average decision cycle for green investments has decreased by 30-40% (Song et al., 2025) [7], accelerating the time-to-sustainability.
- **Political-regulatory level:** Open digital platforms and shared data ecosystems break down barriers to the transfer of green technologies between SMEs, suggesting a need for targeted support from regulators (Mubarak et al., 2025) [16].
- **Research perspective:** There is a lack of longitudinal studies tracking how human-centric elements of I5.0 (D4) impact environmental KPIs and employee well-being; this deficit represents a promising trajectory for future empirical studies.

This extension makes the Digital-Sustainability Nexus framework a practical tool for planning, monitoring, and scaling green innovations in digitally transformed industry.

5 Conclusions

A complex meta-analysis of literature from 2019–2025 confirmed that the success of green innovations in enterprises is conditioned by a triad: environmental determinants (K1-K5), employee competencies, and digital technologies (D1-D5). The resulting "Digital-Sustainability Nexus" shows that:

- K1 Stakeholder-regulatory pressure and K4 Green financing create an external impulse that initiates investment in green solutions; however, their effect is only maximized if the enterprise has strategic green leadership and sustainability-oriented CRM.
- K2 Technological readiness and D1 Cyber-physical integration are interdependent: digital twins and robotics enable the simulation and validation of environmental benefits before implementation.
- K3 Intellectual property and innovation ecosystems are catalysts for open innovation (D5), shortening the time to market for green products..
- K5 Macro-factors (politics, energy prices) modify the pace of adoption; however, the enterprise can reduce volatility through AI-supported strategic foresight (D3+D5).

Specification of employee competencies in creating green innovations as part of the enterprise's technological foresight

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Table 8 Impulses for management and competence development (own processing, 2025)

Level of recommendation	Practical steps	Expected contribution
Strategic	<ul style="list-style-type: none"> • Implementation of a foresight-lab with scenario workshops; • Linking KPIs to environmental metrics through digitally managed dashboards. 	Faster and more qualified investment decision-making; better compliance with ESG regulations.
Organizational	<ul style="list-style-type: none"> • Modular development programs: micro-credentials in data analytics, eco-design, reverse logistics; • Mentoring & job rotation between R&D, production, and logistics. 	Higher internal absorption capacity for 4.0/5.0 technologies; breaking down the silo effect.
Individual	<ul style="list-style-type: none"> • Gamified XR training for collaborative robotics and energy management; • Supporting green intrapreneurship through internal grant schemes. 	Increasing green work engagement and creativity; faster internalization of new skills.

The results indicate that harmonized support for digital infrastructure and green financing (e.g., tax breaks for AI-controlled energy systems) has a multiplier effect on the rate of adaptation of green innovations. Measures should target SMEs, where regulatory pressure often exceeds available resources.

Although the systematic review covers six years and several industrial sectors, quantitative studies from manufacturing are predominant; the service sector is less well represented. Future research could:

1. Conduct long-term analyses of the impact of human-centric Industry 5.0 solutions on environmental KPIs.
2. Explore the intersection of social sustainability (well-being, diversity) with digital technologies and green innovations.
3. Develop a standardized competency index combining ecological, digital, and resilience skills (stress management skills).

The study offers a holistic framework that integrates environmental determinants, employee competencies, and digital technologies into a single coherent model. Enterprises that simultaneously invest in (i) the development of key competencies, (ii) Industry 4.0/5.0 digitalization initiatives, and (iii) strategic foresight achieve a faster and more sustainable innovation trajectory.

This article enriches the discourse on green transformation with empirically based recommendations for management and technological development, while providing a basis for further academic and practical discussion.

Acknowledgement

This article was also created as part of the Young Researcher project No. 1349: "Specification of employee competencies in the implementation of green production principles".

This article was also created as part of the Young Researcher project No. 1347: "Analysis of the application of methodologies and tools for the evaluation of green production in industrial enterprises in the Slovak Republic".

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Review process

Single-blind peer review process.

