



Sustainability oriented innovation pathways in EU regions: The role of Industry 4.0

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SUSTAINABILITY ORIENTED INNOVATION PATHWAYS IN EU REGIONS: THE ROLE OF INDUSTRY 4.0

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SUMMARY

The transition towards digital, sustainable, and resilient regional economies calls for a better understanding of how firms combine technological, organisational, and sustainability-oriented innovations across space. This study examines the determinants of eco-innovation and social innovation in European firms, adopting a multi-level perspective that links firm capabilities to the business environment and regional context. Drawing on firm-level data from Flash Eurobarometer 559, we analyse how digital adoption and organisational innovation, together with firms' perceptions of collaboration networks, workforce skills, and access to finance, shape innovation decisions within heterogeneous regional settings. The results identify digital transformation and organisational innovation as key enablers of both eco- and social innovation. However, important asymmetries emerge: collaboration networks are more strongly associated with eco-innovation, while workforce skills play a more prominent role in social innovation. Joint estimation reveals a positive correlation between both types of innovation, driven by shared unobserved factors, but conditional results suggest potential trade-offs once these are controlled for. Overall, firm-level factors dominate in explaining innovation behaviour, although regional heterogeneity remains significant. These findings highlight the importance of place-sensitive policy approaches that align digitalisation, organisational change, and sustainability transitions across regions.

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1. Introduction

The transition towards sustainable, inclusive, and resilient economic systems has become a central concern in both academic research and European policy agendas. Increasingly, regional development is understood not only in terms of productivity and growth, but also in relation to environmental sustainability and societal well-being. This shift reflects what has been described as a “normative turn” in the geography of innovation, whereby innovation is assessed in terms of its contribution to addressing grand societal challenges (Castellacci et al., 2025). Within this evolving framework, regions are key arenas where technological, environmental, and social transformations interact and co-evolve.

Innovation plays a pivotal role in these transformations. However, the concept of innovation has broadened significantly beyond traditional technological advancements to include environmental and social dimensions. Eco-innovation -defined as the development and application of products, processes, or organizational changes that reduce environmental harm- has become a core element of sustainability transitions (OECD, 2011; Krupoderova and Portnov, 2020). At the same time, social innovation has emerged as a crucial mechanism for addressing societal needs through new forms of collaboration, governance, and social practices (Moulaert and Van den Broeck, 2018). While these two forms of innovation have often been analysed separately, there is growing recognition that they are deeply interconnected and jointly shape the trajectory of regional development.

From a theoretical standpoint, the analysis of sustainability-oriented innovation requires integrating insights from multiple strands of literature. The regional innovation systems (RIS) framework emphasizes the importance of interactions among firms, institutions, and knowledge organizations in shaping innovation capabilities within regions (Asheim and Coenen, 2005; Tödtling and Trippl, 2005; Bai et al., 2024). Complementing this perspective, evolutionary economic geography highlights the role of path dependency, related variety, and regional capabilities in explaining uneven regional development trajectories (Boschma, 2015; Martin and Sunley, 2006). At the firm level, the concept of absorptive capacity -defined as the ability to identify, assimilate, and exploit external knowledge- provides a key micro-foundation for understanding how firms engage in innovation processes (Cohen and Levinthal, 1990). Together, these frameworks suggest that innovation outcomes depend on both firm-level characteristics and region-specific contexts.

In recent years, the emergence of Industry 4.0 technologies has introduced a new layer of complexity to these dynamics. Technologies such as artificial intelligence, advanced robotics, big data analytics, and the Internet of Things are transforming production systems, business models, and organizational structures. This technological shift is widely seen as a new techno-economic paradigm with far-reaching implications for regional economies (De Propris and Bellandi, 2021). While digitalization offers significant opportunities for productivity gains, innovation, and resource efficiency, its diffusion is highly uneven across regions. Differences in skills, infrastructure, institutional quality, and innovation ecosystems mean that not all regions are equally able to benefit from Industry 4.0, potentially exacerbating existing territorial inequalities (UNCTAD, 2021).

The impact of Industry 4.0 on regional development is therefore contingent on local capabilities and transformation pathways. Evolutionary approaches suggest that regions may follow diverse trajectories depending on their ability to adapt, upgrade, or diversify their economic structures in response to technological change (De Propris and Bailey, 2021). In this context, digital transformation can act both as an enabler of sustainability-oriented innovation and as a source of divergence, reinforcing disparities between leading and lagging regions.

Importantly, the relationship between digitalization and sustainability is not automatic. Digital technologies can facilitate eco-innovation by improving resource efficiency, enabling monitoring and optimization, and supporting circular economy practices. However, they may also generate rebound effects or increase inequalities if not accompanied by appropriate organizational and institutional changes. Similarly, social innovation processes are closely linked to organizational practices, human

capital development, and collaborative networks, all of which are deeply embedded in regional contexts. This highlights the need for an integrated analytical framework that considers technological, organizational, and territorial dimensions simultaneously.

The spatial dimension is thus central to understanding sustainability-oriented innovation. A substantial body of literature demonstrates that eco-innovation is shaped by regional factors such as institutional frameworks, collaboration networks, demand conditions, and knowledge spillovers (Losacker et al., 2023). In policy terms, this has led to the increasing prominence of place-based approaches, which emphasize that development strategies must be tailored to the specific characteristics and capabilities of individual regions (Barca, McCann and Rodríguez-Pose, 2012). Such approaches are particularly relevant in the context of sustainability transitions, where local conditions strongly influence innovation pathways.

Despite these advances, important gaps remain in literature. First, empirical studies often focus on single dimensions of innovation -such as eco-innovation or digital innovation- without fully considering their interactions with social innovation processes. Second, while regional heterogeneity is widely acknowledged, there is limited micro-level evidence on how firm behaviour interacts with territorial characteristics to shape sustainability outcomes. Third, SMEs, which constitute the backbone of the European economy, remain underexplored in integrated analyses that combine digital transformation, organizational change, and sustainability-oriented innovation.

This paper seeks to address these gaps by analysing the determinants of eco-innovation and social innovation in SMEs and large firms across European regions. Using firm-level microdata from Flash Eurobarometer 559, we examine how the adoption of Industry 4.0 technologies, together with organizational innovation, collaboration networks, and resilience capacities, influences sustainability-oriented innovation outcomes. Crucially, the analysis explicitly accounts for regional heterogeneity, allowing for the identification of spatially differentiated patterns.

The paper contributes to literature in three main ways. First, it advances a more integrated conceptualization of sustainability-oriented innovation by jointly analysing eco-innovation and social innovation. Second, it bridges firm-level and regional perspectives, linking microeconomic behaviour to territorial dynamics. Third, it provides new empirical evidence on how digital and organizational transformations shape innovation outcomes across heterogeneous regional contexts, offering insights for place-sensitive policy design.

The remainder of the paper is structured as follows. Section 2 reviews the literature and develops hypotheses. Section 3 presents the data and methodology. Section 4 reports empirical results. Section 5 discusses the findings and policy implications, and Section 6 concludes.

2. Literature Review, Hypotheses Development and Theoretical Framework

2.1. Sustainability-Oriented Innovations: integrating eco- and social dimensions

The transition towards sustainability requires moving beyond narrow conceptions of innovation to incorporate both environmental and societal dimensions. Eco-innovation and social innovation represent two complementary pillars of sustainability-oriented innovation, reflecting the dual need to reduce environmental pressures while enhancing social inclusion and well-being. Eco-innovation refers to new or significantly improved products, processes, or organizational methods that reduce environmental harm and resource use (OECD, 2011; Krupoderova and Portnov, 2020), while social innovation involves new forms of social organization, institutional arrangements, and collaborative practices addressing societal challenges (Moulaert and Van den Broeck, 2018).

Although these forms of innovation have typically been analysed independently, recent approaches in the geography of innovation emphasize their interdependence within broader socio-technical transitions (Castellacci et al., 2025). Both rely on new knowledge combinations, organizational

change, and collaboration networks, suggesting that firms engaging in one type of sustainability-oriented innovation are more likely to develop the other.

H1. Eco-innovation and social innovation are positively correlated at the firm level.

2.2 Influence of Firm-level Characteristics on Sustainability-Oriented Innovations

The adoption of sustainability-oriented innovation is shaped by a combination of firm-level capabilities related to technology and organisational capabilities. In this context, the diffusion of Industry 4.0 technologies -such as artificial intelligence, big data, and advanced automation- has transformed firms' innovation capacities and production processes. These technologies enable more efficient use of resources, real-time monitoring of environmental impacts, and optimisation of production systems, thereby fostering eco-innovation. Digitalisation can support circular economy models, reduce energy consumption, and improve environmental performance (De Propris and Bellandi, 2021).

However, the benefits of Industry 4.0 are not automatic, as they depend on firms' capabilities to integrate advanced digital technologies into their innovation processes. Firms with higher absorptive capacity are better able to leverage digital tools for eco-innovation (Cohen and Levinthal, 1990). Empirical evidence suggests that technological capabilities and digital transformation are key drivers of eco-innovation, particularly when combined with complementary organizational changes.

Literature highlights that digital technologies not only contribute to achieve environmental sustainability, but also social sustainability (Ferreira et al, 2023). The implementation of multiple digital technologies can enhance firms' ability to introduce sustainable innovations by harnessing the environmental and social benefits each technology offers as drivers of value creation (Büchi et al., 2020). In this context, digital technologies can be conceptualized as key resources with the potential to contribute positively to the achievement of sustainable development goals -such as sustainable manufacturing, the circular economy, and socio-ecological sustainability- when deployed in innovative ways (Ardito, 2023). In the era of Industry 4.0, some studies reveal that the implementation of cloud computing, data analytics, robotics, artificial intelligence and blockchain contributes to promoting social sustainability in manufacturing firms, by increasing work efficiency and workers' physical and mental health, reducing working hours, enabling multi-tasking or automating routines (Ferreira et al. 2023).

H2. The adoption of Industry 4.0 digital technologies increases the likelihood of sustainability-oriented innovations.

Organisational innovation further complements technological adoption by enhancing firms' flexibility, coordination, and learning processes. Organizational innovation plays a central role in enabling firms to respond to complex sustainability challenges. Changes in organizational structures, management practices, and work organisation can enhance flexibility, foster learning, and facilitate collaboration. These processes are particularly important not only for social innovation -which depends on relational assets, stakeholder engagement, and new governance arrangements- but also for eco-innovation. In the environmental domain, organizational innovation supports the integration of sustainability into business strategies, improves resource efficiency, and facilitates the adoption of cleaner processes and circular practices (Triguero et al., 2025). By promoting cross-functional coordination, employee involvement, and knowledge sharing, it enables firms to identify and implement environmentally friendly solutions more effectively.

Social innovation is often rooted in bottom-linked governance, collective learning, and participatory processes, highlighting the importance of organizational capacities (Moulaert and Van den Broeck, 2018). Firms that adopt innovative organizational practices -such as teamwork, decentralised decision-making, and employee involvement- are better positioned to develop socially innovative solutions.

H3. Organizational innovation increases the likelihood of sustainability-oriented innovations.

2.3 Business environment and place-based effects on sustainability-oriented innovations

Innovation processes are not only driven by firm-level characteristics but are also embedded in business contexts. Differences in institutional quality, knowledge infrastructures, and economic structures influence firms' access to knowledge, resources (human and financial) and support mechanisms.

Regarding the role of business environment, collaboration networks is relevant to access external knowledge and complementary resources. Collaboration is a key driver of innovation, particularly in the context of sustainability transitions, which require the integration of diverse knowledge bases. The RIS literature emphasises the importance of interactions between firms, universities, and public institutions in fostering innovation (Asheim and Coenen, 2005; Tödtling and Trippel, 2005). Collaborative networks enable firms to access external knowledge, share risks, and develop complex innovations. Sustainability practices have led firms to consider the needs and expectations of stakeholders -such as governments, customers, and suppliers -regarding sustainability. This, in turn, facilitates a better integration of economic, social, and environmental dimensions into innovation strategies, while also enabling the acquisition of new social and environmental knowledge to be incorporated into innovation processes (Ardito, 2023).

In the context of eco-innovation, inter-organizational collaboration is particularly important due to the systemic nature of environmental challenges, which often require coordination across supply chains and sectors (Losacker et al., 2023). Similarly, social innovation relies heavily on partnerships with local communities, public actors, and civil society organisations. Collaborative networks have been increasingly employed to promote social innovation in tackling complex societal challenges, while also improving coordination among actors and facilitating the sharing of resources (Wegner et al., 2023). Social innovation is understood as both a process and a product, addressing societal challenges through inclusive and collaborative approaches (Sirolli et al., 2025) which need to directly reflect stakeholder engagement for long-term success and change (Salmon et al., 2025). That implies that social innovation emerges through collaboration with a range of stakeholders, including customers, civil society organizations, local businesses, and researchers. Social firms co-develop ideas alongside these actors, drawing on their diverse resources to address social challenges and build innovative solutions (Tanimoto, 2012).

H4. Engagement in collaboration networks increases the likelihood of sustainability-oriented innovation

Previous literature supports the view that the quality of human capital constitutes a key determinant of sustainability-oriented innovation, encompassing both its environmental and social dimensions. In eco-innovation, several studies provide evidence that workforce capabilities, education and specialization are decisive factors in the development of this type of innovation (Del Río et al., 2016). In this line, Bagagiolo et al. (2023) and Bucur (2024) find that the availability and training of highly qualified workforce represent a relevant driver of eco-innovative processes. The social innovation literature consistently emphasizes a positive association between workforce skills and educational levels and the generation of innovations with social impact (Akgüç, 2020).The

availability of suitable human capital plays a decisive role (Audretsch et al., 2021), since employees' knowledge and capabilities are essential for the generation of innovative solutions to social challenges (Pansuwong et al., 2023).

H5. High-skilled workforce increases the likelihood of sustainability-oriented innovation

The availability of financial resources also represents a critical determinant of both environmental and social innovation, as such activities require substantial upfront investment and the capacity to manage the uncertainty inherent in sustainable transitions. Financial constraints have been consistently identified as a major barrier, significantly reducing firms' likelihood of adopting green technologies, particularly in European manufacturing sectors (Ghisetti et al., 2015). Conversely, access to adequate financing, especially when combining internal resources with public support, facilitates investments in clean technologies and sustainable infrastructures (Cecere et al., 2020). From a resource-based perspective, firms' financial capabilities influence their engagement in sustainability-oriented innovations. Empirical evidence shows that financial capacity positively affects both eco-innovation and social innovation, although its impact appears to be stronger for eco-innovations (Horbach, 2024). Financial resources are also essential for social innovation, as such initiatives require long-term commitment and continuous investment (Cajaiba-Santana, 2014). In this regard, financial slack enables firms to invest in environmental, social, and governance initiatives, thereby enhancing their sustainability performance and capacity to address environmental and social objectives (Heubeck & Ahrens, 2025). Overall, financial resources are not merely an operational enabler but a structural condition for sustainable innovation.

H6. The availability of financial resources increases the likelihood of sustainability-oriented innovation

The regional innovation systems framework highlights how territorial dynamics shape innovation performance, while evolutionary economic geography emphasises the role of path dependency and local capabilities in shaping regional trajectories. Empirical evidence shows that environmental and social innovation are influenced by regional factors such as collaboration intensity, institutional frameworks, and local demand conditions (Losacker et al., 2023). This implies that firms operating in different regions may face heterogeneous opportunities and constraints that affect their propensity to innovate. At the same time, place-based approaches argue that development policies must be tailored to regional characteristics to be effective (Barca, McCann and Rodríguez-Pose, 2012).

H7. The regional heterogeneity influences the likelihood of sustainability-oriented innovation

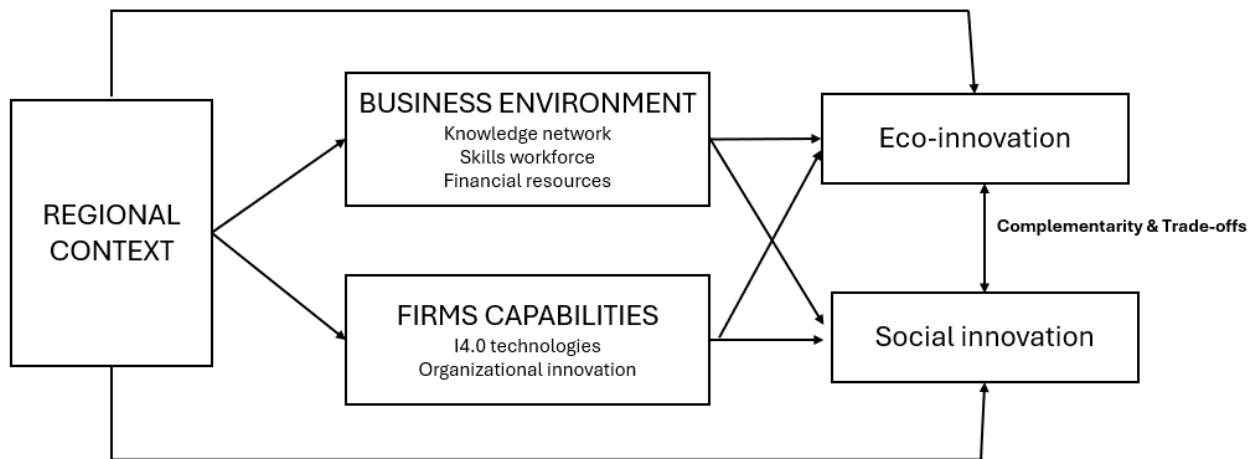
2.3. Theoretical framework

Building on the previous discussion, this paper proposes an integrated theoretical framework in which eco-innovation and social innovation are jointly determined by the interaction between firm-level capabilities, business environment conditions, and regional contexts. While existing literature has often treated these dimensions separately, we conceptualise sustainability-oriented innovation as a multi-dimensional process in which different innovation outcomes emerge from a shared capability base but may also compete for limited organisational resources.

Drawing on the absorptive capacity perspective (Cohen and Levinthal, 1990; Zahra and George, 2002) and the dynamic capabilities framework (Teece, 2007), we argue that the ability to identify, assimilate, and exploit knowledge underpins both eco-innovation and social innovation. In this

context, adoption of Industry 4.0 technologies enhances firms' capacity to process and utilise information and organisational innovation increases their ability to reconfigure internal processes enabling learning and knowledge recombination. At the same time, firms operate within a broader business environment that conditions their access to external knowledge and resources. Collaboration networks provide channels for knowledge exchange and collective learning, which are particularly relevant for eco-innovation and social innovation due to its technological and systemic nature. High-skilled workforce also favours the adoption of both types of innovations. Access to finance also relaxes resource constraints and enables firms to invest in innovation activities, especially in the presence of uncertainty and long-term returns. These meso-level factors do not determine innovation outcomes directly but shape the effectiveness with which firms can mobilise their internal capabilities. Finally, regional contexts influence innovation processes through institutional frameworks, knowledge infrastructures, and economic structures at the macro-level. However, in line with recent critiques of territorially deterministic approaches, we posit that regional effects operate primarily as enabling or constraining conditions, rather than as primary drivers of firm behaviour. Figure 1 summarises the theoretical framework. Sustainability-oriented innovation is jointly determined by firm-level capabilities, business environment conditions, and regional context. While both eco-innovation and social innovation share common drivers, their relationship reflects the coexistence of complementarities and trade-offs, as firms allocate limited capabilities across different innovation domains.

Figure 1 – Sustainability-oriented innovation: drivers and trade-offs



Source: own elaboration

3. Data, Variables and Econometric Strategy

3.1 Data and variables

The empirical analysis is based on firm-level microdata from Flash Eurobarometer 559: “*Startups, scaleups and entrepreneurship*”, conducted by the European Commission. The survey was carried out between February and April 2025 and provides a representative sample of firms across EU Member States. The survey contains detailed information on firms' adoption of advanced technologies, organisational practices, and engagement in environmental and social innovation activities, making it particularly well suited for analysing sustainability-oriented innovation.

Following the conceptual framework, two dependent variables are constructed to capture firms' engagement in different forms of innovation: eco-innovation and social innovation.

Eco-innovation ($EcoInnov_i$) is defined using survey questions that capture firms' adoption of environmentally oriented innovations. In particular, the measure is based on firms' responses to

whether they have introduced an innovation with an environmental benefit, including innovations with an energy or resource efficiency benefit. A binary variable is therefore constructed, taking the value of 1 if firm i engages in eco-innovation, and 0 otherwise. This operationalisation encompasses actions such as the introduction of environmentally friendly products or services, the adoption of resource-efficient production processes, and initiatives aimed at reducing energy use, waste, or emissions, and is consistent with the OECD (2007) definition of eco-innovation.

Social innovation ($SocInnov_i$) is proxied using survey questions that capture firms' adoption of socially oriented practices. Specifically, firms are asked whether they have introduced social innovations, understood as new products, services, or processes that aim to improve society. Based on this information, a binary indicator is constructed, equal to 1 if firm i reports engaging in such practices, and 0 otherwise. This measure captures actions such as the introduction of organisational practices aimed at improving employee well-being, initiatives targeting social inclusion or community engagement, and changes in work organisation, including increased flexibility or participation.

The empirical specification also incorporates a set of variables capturing both internal resources and external environmental conditions, in line with the theoretical framework derived from the resource-based view and the literature on innovation systems. These variables are expected to shape firms' propensity to engage in eco-innovation and social innovation through distinct but complementary mechanisms.

First, technological and organisational capabilities are captured through the adoption of Industry 4.0 technologies ($i40$) and organisational innovation. Second, the analysis incorporates variables related to the external business environment, capturing firms' perception. Network embeddedness ($Network$) is derived from firms' assessment of their access to and collaboration with business partners, including other enterprises, public sector organisations, and research institutions. Human capital availability ($Skills$) is based on firms' evaluation of the availability of staff with the right skills, including managerial skills. Finally, financial conditions (Fin_access) capture firms' perceived access to private and public finance. All the variables related to business environment are measured on a Likert scale ranging from 1 to 4, where higher values indicate more favourable conditions. As such, they capture firms' perceptions of the opportunities and constraints present in their business environment, complementing internal firm-level characteristics.

Lastly, the model includes control variables to reflect structural differences across firms, such as firm size (measured as the logarithm of employment) and firm age (measured as the logarithm of years since establishment). Larger and more experienced firms are typically expected to exhibit higher innovation capabilities due to greater access to resources and accumulated knowledge. In addition, sectoral and regional (NUTS2) fixed effects are included to control for industry-specific characteristics and unobserved territorial heterogeneity.

3.2. Baseline model: firm-level determinants with regional fixed effects

Given the binary nature of the dependent variables, the empirical analysis relies on probit-type models to estimate the likelihood that firm i , located in region r , engages in Eco-Innovation or Social-Innovation. The baseline specifications are defined as:

$$\Pr(EcoInnov_i = 1) = \Phi(\alpha_1 + \beta_1 i40_i + \beta_2 org_innov_i + \beta_3 Networks_i + \beta_4 Skills_i + \beta_5 Fin_access_i + \beta_6 employees_i + \beta_7 lage_i + \eta_{s(i)} + \mu_{r(i)}) \quad [1]$$

$$\Pr(SocialInnov_i = 1) = \Phi(\alpha_1 + \beta_1 i40_i + \beta_2 org_innov_i + \beta_3 Networks_i + \beta_4 skills_i + \beta_5 Fin_access_i + \beta_6 employees_i + \beta_7 lage_i + \eta_{s(i)} + \mu_{r(i)}) \quad [2]$$

where $\Phi(\cdot)$ denotes the cumulative standard normal distribution function. The variable $i40_i$ captures technological innovations related to digitalization, $network4_i$ reflects firms' network embeddedness, $cualif4_i$ captures human capital constraints and $fin4_i$ includes financial constraints. l , firm size ($lempleo_i$), and firm age ($lage_i$). Sector fixed effects are denoted by $\eta_{s(i)}$, while $\mu_{r(i)}$ captures unobserved, time-invariant heterogeneity at the NUTS2 regional level. All models are estimated by maximum likelihood. Standard errors are clustered at the NUTS2 level to account for spatial correlation in unobserved shocks affecting firms operating within the same regional environment.

Given the potential interdependence between Eco-innovation and social innovation, the empirical strategy further employs a bivariate probit model:

$$\begin{aligned} EcoInnov_i^* &= Z_i' \beta_1 + \varepsilon_{1i} \\ SocialInnov_i^* &= Z_i' \beta_2 + \varepsilon_{2i} \end{aligned} \quad [3]$$

with:

$$\text{Cov}(\varepsilon_{1i}, \varepsilon_{2i}) = \rho \quad [4]$$

A statistically significant correlation coefficient ρ indicates that both innovation decisions are jointly determined by common unobserved factors. To further investigate this relationship, a recursive bivariate probit specification is estimated, in which eco-innovation enters directly into the social innovation equation. This specification makes it possible to move beyond simple correlation and to explore the potential directional linkage between both types of innovation.

3.3 Regional heterogeneity and identification of territorial effects

While regional heterogeneity is already controlled for through the inclusion of NUTS2 fixed effects, the analysis is extended to disentangle the contribution of territorial factors to both innovation decisions.

First, a multilevel (hierarchical) probit model is estimated separately for both types of innovation:

$$EcoInnov_i^* = \alpha_1 + X_i' \beta_1 + u_{r(i)} + \varepsilon_{1i} \quad [5]$$

$$SocialInnov_i^* = \alpha_2 + X_i' \beta_2 + u_{r(i)} + \varepsilon_{2i}$$

where $u_{r(i)} \sim N(0, \sigma_r^2)$ captures unobserved regional effects and $\varepsilon_{ki} \sim N(0,1)$ represents the firm-level error term. From these specifications, the intraclass correlation coefficient (ICC) is computed as:

$$ICC = \frac{\sigma_r^2}{\sigma_r^2 + 1} \quad [6]$$

The ICC provides a direct measure of the proportion of total variation in eco-innovation and social innovation attributable to differences across regions, allowing a formal assessment of the importance of territorial factors. Second, a within-between (hybrid) specification is implemented to disentangle firm-level and regional-level mechanisms for both innovation types. Each explanatory variable is decomposed as:

$$X_i = (X_i - \bar{X}_{r(i)}) + \bar{X}_{r(i)} \quad [7]$$

where the first term captures within-region variation (firm-level effects) and the second term captures between-region variation (regional context). The resulting models are:

$$\text{EcoInnov}_i = \alpha_1 + \beta_1^W (X_i - \bar{X}_{r(i)}) + \beta_1^B \bar{X}_{r(i)} + \eta_{s(i)} + \varepsilon_{1i} \quad [8]$$

$$\text{SocialInnov}_i = \alpha_2 + \beta_2^W (X_i - \bar{X}_{r(i)}) + \beta_2^B \bar{X}_{r(i)} + \eta_{s(i)} + \varepsilon_{2i} \quad [9]$$

This approach allows identifying whether the observed relationships are primarily driven by firm-level heterogeneity within regions or by systematic differences across regional environments. Finally, a control function approach is implemented as a complementary strategy. Residuals obtained from the eco-innovation equation are included in the social innovation model, allowing identification of whether unobserved factors influencing eco-Innovation also affect social innovation. This approach captures the potential presence of cumulative or mutually reinforcing innovation dynamics.

4. Empirical Results

4.1 Descriptive statistics

Table 1 reports descriptive statistics for the main variables used in the analysis. Eco-innovation is observed in 23.51% of SMEs, while social innovation is reported by 20.25%, indicating that sustainability-oriented innovation is relatively widespread but far from universal among European firms. The adoption of at least one Industry 4.0 technology is reported by 67.19% of firms, suggesting that digital transformation has become a relevant feature of firms' strategies, although its intensity varies considerably.

This heterogeneity is clearly illustrated by the variable *total_i40*, which measures the number of Industry 4.0 technologies adopted by each firm (ranging from 0 to 7). While the mean value is 1.477, the standard deviation is relatively high (1.356), indicating a highly uneven distribution of digital adoption intensity across firms. In practice, this implies that although a large share of firms has adopted some form of digital technology, most firms rely on a limited and selective set of technologies, whereas only a smaller group of firms engages in more advanced and comprehensive Industry 4.0 strategies. This pattern points to significant heterogeneity in digital advanced technologies related to 4th Industrial Revolution.

Organisational innovation is reported by 16.56% of firms, suggesting that changes in organisational practices are less widespread than technological adoption related to eco-innovations or to social innovations, despite their importance for sustainability-oriented innovation.

Several explanatory variables are measured on Likert-type scales ranging from 1 to 4, capturing firms' perceptions of different dimensions of their business environment. The variable *Network*, which reflects the intensity of collaboration and networking activities, exhibits the highest mean value (2.694) among the Likert-scale variables. This suggests that firms are, on average, relatively active in cooperation and external linkages, underlining the importance of relational assets within their business environment. The variable *Skills*, capturing the availability of qualified human capital, reports a mean value of 2.463, indicating a moderate-to-high level of workforce capabilities. However, its standard deviation (0.973) points to non-negligible heterogeneity across firms in terms of skill endowments. Finally, *Fin_access*, reflecting firms' access to financial resources, has a mean value of 2.267. This value lies slightly above the midpoint of the scale, suggesting that, on average, firms perceive financial conditions as moderately favourable, although the relatively high dispersion (sd = 1.226) indicates substantial variability across firms. This finding is consistent with the presence of financial constraints affecting a non-negligible share of firms.

Table 1 - Descriptive statistics

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
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Eco-innovation	13,787	0.235	0.424	0	1
Social- innovation	13,787	0.203	0.402	0	1
i40	13,787	0.672	0.470	0	1
total_i40	13,787	1.477	1.356	0	7
Org_innov	13,787	0.166	0.372	0	1
Network	13,787	2.694	1.097	0	4
Skills	13,787	2.463	0.973	0	4
Fin_access	13,787	2.267	1.226	0	4
# of employees	13,648	99.42	986.6	1	88000
Age	13,232	30.20	29.35	1	326

Overall, these descriptive statistics reveal substantial heterogeneity across firms, not only in innovation outcomes but also in the adoption of advanced digital technologies, organisational practices, and key dimensions of the business environment. This evidence supports the importance of accounting for both firm-level diversity and contextual factors in the subsequent econometric analysis. Correlation coefficients (Table A.1 in the Appendix) show a positive and statistically significant association between eco-innovation and social innovation, providing initial support for H1. In addition, variance inflation factors (Table A.2) indicate no concerns of multicollinearity (VIF < 5).

Table 2 highlights clear and systematic differences across firm size. In general, larger SMEs exhibit higher levels of sustainability-oriented innovation. The incidence of eco-innovation increases from 19.2% among micro firms to 28.2% among medium-sized firms, while social innovation follows a similar pattern, rising from 18.6% to 23.1%.

A comparable pattern emerges for digitalisation. Both the adoption of Industry 4.0 technologies and their intensity increase with firm size. While 62.0% of micro firms report adopting such technologies, this share rises to 72.5% among medium-sized enterprises. Similarly, the average number of technologies used increases progressively, indicating that larger firms not only adopt digital tools more frequently but also integrate them more extensively into their operations. Organisational innovation also increases with firm size, although differences are more moderate. In parallel, variables capturing dimensions of the business environment -namely collaboration intensity, workforce skills, and financial conditions- consistently show higher average values for larger firms. This pattern underscores the role of resource availability and relational assets in shaping firms' innovation decisions. Taken together, these results suggest that firm size is a key determinant of both innovation capabilities and sustainability-oriented outcomes. Larger firms appear better positioned to adopt Industry 4.0 technologies, engage in collaborative networks, and implement organisational changes, thereby enhancing their propensity to innovate in both environmental and social domains.

Table 2 - Descriptive statistics by firm size

	(1) Micro		(2) Small		(3) Medium	
	<i>mean</i>	<i>sd</i>	<i>mean</i>	<i>sd</i>	<i>mean</i>	<i>sd</i>
Eco-innovation	0.192	0.394	0.233	0.422	0.282	0.450
Social- innovation	0.186	0.389	0.194	0.396	0.231	0.422
i40	0.620	0.485	0.688	0.464	0.725	0.446
total_i40	1.295	1.286	1.475	1.317	1.688	1.407
Org_innov	0.138	0.345	0.171	0.377	0.192	0.394
Network	2.623	1.148	2.717	1.070	2.766	1.043
Skills	2.393	1.046	2.480	0.925	2.538	0.914
Fin_access	2.150	1.237	2.312	1.210	2.367	1.208
# of employees	3.786	2.46	21.74	11.036	107.30	52.235
Age	25.193	24.52	30.11	27.982	37.35	34.479
Observations	5385		4864		2502	

The classification of EU NUTS-2 regions into four innovation profiles reveals a highly heterogeneous spatial landscape across the EU-27 (Table 4). Overall, a large share of regions (37.5%) falls into the laggard category, characterised by low levels of both eco-innovation and social innovation, suggesting the presence of structural limitations in regional innovation systems. These lagging regions are widely distributed across Southern and Eastern Europe, as well as parts of Central Europe. For instance, several regions in Greece (e.g. GR_11, GR_8), Italy (e.g. IT_20, IT_16), and Croatia (HR_1, HR_2), together with regions in Bulgaria, Latvia and Lithuania, exhibit consistently low innovation performance. Notably, laggard profiles are also present in some more advanced economies, including Germany (e.g. DE_8, DE_9) and France (FR_15, FR_22), indicating that low sustainability-oriented innovation is not exclusively associated with less developed countries but may also reflect intra-national disparities.

A second group of regions (17.5%) displays a clear eco-oriented profile, characterised by above-average eco-innovation but comparatively weaker social innovation. These regions are often located in Central and Northern Europe, including parts of Austria (AT_1, AT_2), Denmark (DK_1, DK_2), and the Czech Republic (CZ_2, CZ_6), as well as several Polish regions (e.g. PL_1, PL_6) and some regions in Portugal (e.g. PT_2). This pattern suggests a stronger emphasis on technologically driven eco-innovation, likely supported by industrial structures and regulatory frameworks that promote efficiency and resource optimisation.

In contrast, 15.9% of regions are classified as social-oriented, exhibiting relatively higher levels of social innovation but lower eco-innovation. These regions are more frequently found in Southern and peripheral areas, as well as in some Central European economies. Examples include regions in Spain (ES_3, ES_10), Greece (GR_2, GR_4), and Portugal (PT_4), alongside regions in Eastern Europe such as Romania (RO_2, RO_7) and Bulgaria. In these contexts, innovation appears to be more strongly driven by organisational change, social needs, and relational assets rather than by technological upgrading.

Finally, a substantial share of regions (29.1%) emerges as innovation leaders, combining high levels of both eco-innovation and social innovation. These leading regions are predominantly concentrated in Western and Northern Europe, notably in the Netherlands (e.g. NL_3, NL_5, NL_8), Belgium (multiple regions such as BE_1, BE_5, BE_9), Ireland (IE_1, IE_5), and Luxembourg (LU_1, LU_3). In addition, several regions in France (FR_1, FR_2, FR_11), Spain (ES_1, ES_9), and Portugal (PT_1, PT_3) also belong to this group. These regions are characterised by well-developed innovation systems, strong institutional environments, and the ability to combine technological capabilities with organisational and social innovation processes.

Taken together, these results point to the existence of highly differentiated regional innovation pathways across the EU-27. Rather than a uniform pattern, regions specialise in distinct combinations of eco-innovation and social innovation, reflecting differences in economic structure, institutional quality, and absorptive capacity. This spatial heterogeneity reinforces the argument that sustainability transitions are inherently place-dependent and underscores the need for tailored, place-based policy approaches capable of addressing region-specific constraints and opportunities.

Table 4 - Classification of regions according to eco-innovation and social innovation

	(1) Freq.	(2) Percent
Laggards (low eco / low social)	94	37.45
Eco-oriented	44	17.53
Social-oriented	40	15.94
Leaders (high eco / high social)	73	29.08
# of regions	251	100.00

4.1. Econometric Results

Table 5 presents the results of the bivariate probit model, which jointly estimates eco-innovation and social innovation while allowing for correlation in their unobserved determinants. Three sets of specifications are reported. Columns (1) and (2) show the baseline estimates, columns (3) and (4) report the same specification with clustered standard errors, and columns (5) and (6) present the recursive model, in which eco-innovation is explicitly included as an explanatory variable in the social innovation equation.

Across all specifications, the estimated correlation coefficient (ρ) is positive and statistically significant, indicating that both innovation outcomes are driven by common unobserved factors. This finding provides strong support for the presence of complementarities between eco-innovation and social innovation and justifies the use of a joint modelling approach (H1).

Turning to the main explanatory variables, Industry 4.0 adoption (*i40*) and organisational innovation (*Org_innov*) are positive and highly significant in all specifications. This confirms their role as key drivers of both types of sustainability-oriented innovation and suggests that digitalisation and organisational capabilities act as enabling factors across domains. Hence, we accept H2 and H3.

Table 5 - Bivariate probit estimates and interdependence between eco-innovation and social innovation

	(1)	(2)	(3)	(4)	(5)	(6)
	Eco-innovation	Social innov.	Eco-innovation	Social innov	Eco-innov	Social innov
	(Baseline)		(Clustered)		(Recursive)	
Eco-innovation						-0.589*** (0.202)
i40	0.261*** (0.0274)	0.226*** (0.0282)	0.261*** (0.0312)	0.226*** (0.0333)	0.260*** (0.0313)	0.260*** (0.0327)
Org_innov	0.474*** (0.0310)	0.475*** (0.0315)	0.474*** (0.0386)	0.475*** (0.0349)	0.476*** (0.0381)	0.531*** (0.0367)
Network	0.0343*** (0.0117)	-0.00989 (0.0118)	0.0343*** (0.0122)	-0.00989 (0.0124)	0.0343*** (0.0121)	-0.000216 (0.0125)
Skills	9.71e-05 (0.0129)	0.0422*** (0.0133)	9.71e-05 (0.0131)	0.0422*** (0.0132)	0.000626 (0.0131)	0.0366*** (0.0127)
Fin_access	0.0269*** (0.0103)	0.0360*** (0.0106)	0.0269** (0.0108)	0.0360*** (0.0117)	0.0272** (0.0108)	0.0378*** (0.0112)
Log (employees)	0.0679*** (0.00750)	0.0359*** (0.00772)	0.0679*** (0.00891)	0.0359*** (0.00917)	0.0678*** (0.00887)	0.0480*** (0.00985)
Log (age)	0.0345** (0.0151)	-0.00631 (0.0154)	0.0345** (0.0141)	-0.00631 (0.0175)	0.0346** (0.0141)	0.00309 (0.0171)
Constant	-1.565*** (0.106)	-1.188*** (0.104)	-1.565*** (0.118)	-1.188*** (0.112)	-1.570*** (0.118)	-1.125*** (0.116)
Observations	13,106		13,106		13106	
rho (ρ)	0.3540*** (0.0155)		0.3700*** (0.0181)		0.6856*** (0.1129)	
Wald test of rho = 0 (chi2)	461.553		318.507		15.5118	
Prob>chi2	0.0000		0.0000		0.0001	
Log likelihood	-12943		-12943		-12942	
Wald chi2	983.9		603.2		694.6	
Prob > chi2	0.0000		0.0000		0.0000	

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sector and NUTS2 regional fixed effects are included in all specifications.

Notable asymmetries emerge across innovation types. Network collaboration is positive and statistically significant only for eco-innovation, while remaining insignificant for social innovation. In contrast, workforce skills are not significant for eco-innovation but are positive and highly significant for social innovation. These results point to differentiated mechanisms underlying each

type of innovation activity. These results provide partial support for both H4 and H5: collaboration networks are only significant for eco-innovation, whereas a high-skilled workforce is only significant for social innovation. Access to finance consistently shows a positive and significant effect in both equations, indicating that financial constraints remain an important barrier (H6 is accepted).

A key additional insight arises from the recursive specification. When eco-innovation is included directly in the social innovation equation (columns 5 and 6), its coefficient is negative and statistically significant. This suggests that, conditional on observable characteristics and shared unobservable characteristics, firms engaging in eco-innovation may be less likely to undertake social innovation, which is consistent with the presence of trade-offs or resource allocation constraints. Taken together with the positive correlation coefficient (ρ), the results point to a nuanced relationship in which common underlying drivers coexist with potential conditional substitution effects.

As a robustness check, we estimate the recursive specification in the reverse direction, including social innovation in the eco-innovation equation. While these results should not be given a strict causal interpretation, they display a similar pattern and are consistent with the existence of trade-offs between the two innovation activities. These estimates are reported in the Appendix Table A.4.

Table 6 presents multilevel probit estimates that explicitly account for regional clustering at the NUTS-2 level. The results confirm the robustness of the firm-level drivers identified in the baseline models. However, the estimated intraclass correlation coefficients (ICC) are extremely small for both types of innovations. The estimated intraclass correlation coefficients (ICC) are extremely small for both eco-innovation ($4.95e-05$) and social innovation ($5.67e-05$), indicating that none of the total variation in innovative decisions can be attributed to differences across NUTS2 regions. Instead, the results suggest that almost all variation is driven by firm level characteristics rather than regional context.

Table 6 - Multilevel probit estimates of eco-innovation and social innovation: regional effects

	(1) Eco-Innovation (Multilevel Probit)	(2) Social-Innovation (Multilevel Probit)
i40	0.267*** (0.0281)	0.241*** (0.0290)
Org_innov	0.454*** (0.0316)	0.459*** (0.0321)
Network	0.0382*** (0.0120)	-0.00167 (0.0122)
Skills	-0.00288 (0.0132)	0.0355*** (0.0136)
Fin_access	0.0253** (0.0105)	0.0282*** (0.0108)
Log (employment)	0.0655*** (0.00766)	0.0344*** (0.00792)
Log (age)	0.0356** (0.0155)	1.45e-05 (0.0158)
Constant	-1.580*** (0.109)	-1.208*** (0.107)
Observations	13,106	13,106
Number of groups (NUTS2)	251	251
Variance of random intercept (NUTS2)	0.0346*** (0.00704)	0.0377*** (0.00753)
LR test vs. probit model(p-value)	86.06 (0.000)	91.94 (0.000)
ICC (NUTS2)	4.95e-05	5.67e-05
Log likelihood	-6775	-6309

Notes: Standard errors in parentheses. Multilevel at the NUTS2 regions. ICC refers to the intra-class correlation coefficient. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

These findings do not support H7. While earlier descriptive evidence suggested the existence of spatial heterogeneity, the multilevel results indicate that, once firm-level characteristics are controlled for, regional context has only a minimal direct influence on firms' innovation behaviour. The estimated variance of the regional random effect is very small, resulting in a near-zero intra-class correlation coefficient. This indicates that most of the variation in both eco-innovation and social innovation occurs at the firm level rather than at the regional level.

One possible explanation is that firm-level characteristics, such as the adoption of Industry 4.0 technologies and organisational innovation, play a dominant role in shaping innovation outcomes. In addition, the inclusion of detailed firm-level controls and sectoral fixed effects may capture a substantial share of cross-regional heterogeneity, leaving limited residual variation to be explained at the regional level.

Table 7 reports the results of the hybrid (within-between) modelling approach, which decomposes explanatory variables into within-region and between-region components. This specification allows us to distinguish between differences across firms operating within the same region and structural differences across regions. The results indicate that most explanatory variables primarily operate through within-region variation, suggesting that sustainability-oriented innovation is largely driven by firm-level differences within the same regional environment. In particular, Industry 4.0 adoption, organisational innovation, and financial access display strong and significant within-region effects across both eco-innovation and social innovation.

At the same time, some variables exhibit significant between-region effects, pointing to the role of regional characteristics in shaping innovation outcomes. Notably, organisational innovation shows large and significant between-region coefficients, while financial access and firm size also display relevant between-region variation, particularly for social innovation. This suggests that regions with more favourable structural conditions may systematically support higher levels of innovation.

The results also reveal asymmetries across innovation types. For eco-innovation, network collaboration is significant only through within-region variation, indicating that differences across firms in the same region are key. In contrast, for social innovation, workforce skills show both within- and between-region effects, highlighting the importance of human capital not only at the firm level but also as a regional structural characteristic.

Overall, these findings provide partial support for H7. While regional differences matter in shaping certain structural conditions, the dominant source of variation lies within regions, reinforcing the conclusion that sustainability-oriented innovation is primarily driven by firm-level capabilities operating within a given territorial context.

To assess the robustness of the results to potential endogeneity, a control function approach is implemented. The results, reported in Table A.4, provide evidence of unobserved factors jointly influencing both eco-innovation and social innovation. In particular, the coefficient associated with the residual term ($uhat_{eco}$) is positive and statistically significant, confirming the presence of endogeneity in the baseline estimates. This finding suggests that eco-innovation is correlated with omitted variables that also affect social innovation.

For comparison purposes, separate probit estimations for each innovation decision yield qualitatively similar results and are also presented in Appendix Table A5, together with the full set of sectoral coefficients, which are omitted here for brevity. These additional analyses further support the robustness of the main findings.

Table 7 - Hybrid (within-between region) estimates of eco-innovation and social innovation

(1)

(2)

	Eco-Innovation (Hybrid)	Social-Innovation (Hybrid)
i40_w	0.257*** (0.0318)	0.234*** (0.0332)
mean_i40	0.263 (0.165)	0.165 (0.173)
Org_innov_w	0.429*** (0.0391)	0.428*** (0.0361)
mean_Org_innov	1.496*** (0.248)	1.562*** (0.255)
Network_w	0.0443*** (0.0116)	0.00559 (0.0117)
mean_Network	0.00213 (0.0651)	-0.0729 (0.0656)
Skills_w	-0.00603 (0.0125)	0.0287** (0.0122)
mean_Skills	0.0188 (0.0782)	0.152** (0.0755)
Fin_access_w	0.0227** (0.0105)	0.0220* (0.0113)
mean_Fin_access	0.0585 (0.0650)	0.249*** (0.0596)
Log (employment)_w	0.0606*** (0.00914)	0.0296*** (0.00891)
mean_Log (employment)	0.180*** (0.0482)	0.102** (0.0499)
Log (age)_w	0.0351** (0.0141)	0.00231 (0.0169)
mean_Log (age)	-0.0186 (0.0805)	-0.171** (0.0780)
Constant	-1.909*** (0.400)	-1.589*** (0.384)
Observations	13106	13,106
Log likelihood	-6786	-6304
Wald chi2	435.5	467.2
Prob > chi2	0.0000	0.0000

Notes: Explanatory variables are decomposed into within-region components (deviations from regional means, denoted by “_w”) and between-region components (regional averages, denoted by “mean_”). This specification allows us to distinguish firm-level differences within regions from structural differences across regions. Standard errors are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Regarding control variables, firm size measured by the logarithm of employment is positive and highly significant across all specifications, indicating that larger firms are more likely to innovate in both dimensions. Firm age, however, displays a more nuanced pattern: it is positive and statistically significant in all eco-innovation specifications, but not significant for explaining social innovation models. This suggests that experience and accumulated capabilities matter for eco-innovation, while they do not play a decisive role in explaining social innovation. Finally, the sectoral dummies reveal substantial heterogeneity across industries. Several sectors exhibit significantly higher probabilities of eco-innovation, while for social innovation many sector coefficients are negative and significant, indicating lower relative propensity compared to the reference category. Overall, these results underline the importance of sectoral structure in shaping firms’ innovation behaviour.

5. DISCUSSION AND POLICY IMPLICATIONS

5.1 Interpreting sustainability-oriented innovation: complementarities and trade-offs

The empirical results confirm that eco-innovation and social innovation are interrelated dimensions of sustainability-oriented innovation rather than independent processes. The positive correlation identified in the joint estimation suggests that both are shaped by shared underlying capabilities and strategic orientations, supporting the view of innovation as a multidimensional and co-evolving process. However, this interdependence is not homogeneous. The evidence reveals clear asymmetries in their drivers, pointing to the existence of conditional complementarities. While Industry 4.0 adoption and organisational innovation exert a consistent influence on both types of innovation, other factors operate differently. Collaboration networks are mainly associated with eco-innovation, whereas workforce skills play a more prominent role in social innovation.

These patterns indicate that eco- and social innovation rely on partially distinct knowledge bases and mechanisms. Eco-innovation tends to depend on external linkages and inter-organisational knowledge flows (Cainelli et al., 2015; De Marchi, 2022; Triguero et al., 2025), while social innovation is more closely linked to internal competences, organisational practices, and human capital (Kogut and Zander, 1992; Subramaniam and Youndt, 2005). This distinction highlights the importance of absorptive capacity (Cohen and Levinthal, 1990), as firms differ in their ability to translate external knowledge into innovation outcomes.

From a theoretical perspective, these findings align with the dynamic capabilities' framework (Teece, 2007), which emphasises firms' ability to integrate, reconfigure, and deploy resources. Crucially, the coexistence of a positive correlation and a negative conditional effect in the recursive specification suggests that firms face trade-offs in the allocation of these capabilities. Sustainability-oriented innovation therefore reflects not only shared drivers but also constraints in the simultaneous deployment of resources across multiple domains.

Although regional and contextual factors shape innovation opportunities, their overall effect appears limited. The low regional variance reinforces a firm-centred explanation, in which innovation outcomes depend primarily on internal capabilities rather than location-specific conditions. These findings challenge territorially deterministic interpretations while remaining consistent with evolutionary perspectives on heterogeneous and path-dependent innovation trajectories.

5.2 Digital transformation as an enabler with uneven effects

The results confirm that Industry 4.0 adoption and organisational innovation act as key drivers of both eco-innovation and social innovation, highlighting the central role of technological and organisational capabilities in sustainability-oriented innovation. However, a clear asymmetry emerges in the relevance of business environment factors: collaboration networks are significantly associated only with eco-innovation, while workforce skills are more strongly linked to social innovation.

This pattern can be interpreted in relation to differentiated knowledge bases (Asheim and Gertler, 2005). Eco-innovation is more closely associated with analytical and synthetic knowledge, which relies on scientific and technical expertise and benefits from external knowledge sourcing through inter-organisational networks (Cainelli et al., 2015; Triguero et al., 2025). In contrast, social innovation depends more heavily on experiential knowledge and human capital, which are embedded within the firm and developed through learning processes and internal capabilities from workforce (Kogut and Zander, 1992; Subramaniam and Youndt, 2005).

In this context, digitalisation and organisational innovation provide a shared capability base, but their effectiveness depends on how firms combine them with specific complementary resources. External knowledge linkages are more relevant for eco-innovation, whereas internal skills and organisational processes play a more decisive role in fostering social innovation.

5.3 Policy implications: towards place-sensitive sustainability strategies

The findings of this paper have several implications for policy design at both the European and regional levels. First, they point to the need for a closer alignment between digital and sustainability agendas. While often addressed separately, increasing evidence suggests that digitalisation-particularly Industry 4.0 technologies- can act as a key enabler of eco-innovation and environmental performance (Frank et al., 2019; De Marchi et al., 2022). However, the results also indicate that digitalisation alone is insufficient, as its effectiveness depends on complementary capabilities such as organisational change, skills, and knowledge diffusion.

Second, the evidence highlights the need to broaden innovation policy beyond technological R&D. In line with the literature, innovation outcomes -especially those related to social and sustainability objectives- depend on organisational capabilities, managerial practices, and internal processes (Damanpour, 2014). Social innovation is shaped by both firm-level resources and interactions with external stakeholders, reinforcing the importance of investing in human capital, organisational upgrading, and learning processes (OECD, 2011).

Third, the findings confirm the relevance of collaboration networks and regional innovation ecosystems. This aligns with the regional innovation systems (RIS) literature, which emphasises interactive learning and the role of networks and institutions in shaping innovation dynamics (Asheim & Gertler, 2005; Cooke et al., 1997). Strengthening linkages between firms, universities, and public actors through clusters, partnerships, and knowledge-sharing platforms remains essential to support both eco-innovation and social innovation processes.

Finally, the presence of strong regional heterogeneity supports the adoption of place-based policy approaches. Innovation processes are widely recognised as path-dependent and embedded in local institutional and economic structures (Boschma, 2005; Rodríguez-Pose, 2013). This implies that policy interventions should be tailored to regional conditions. Less developed regions should prioritise absorptive capacity, institutional quality, and SME upgrading, while more advanced regions can focus on scaling up frontier digital and green technologies. Such differentiated strategies are essential to avoid reinforcing territorial disparities and to foster more balanced and inclusive development trajectories.

6. Conclusions

This paper has examined the determinants of sustainability-oriented innovation in European SMEs, focusing on the interplay between digital transformation, organisational change, and regional context. By jointly analysing eco-innovation and social innovation, the study provides novel insight into the multidimensional nature of innovation processes.

The results yield three main conclusions. First, eco-innovation and social innovation are interdependent, confirming that sustainability-oriented innovation is a systemic phenomenon. Second, their drivers differ: digitalisation and organisational change support both, but eco-innovation relies more on external knowledge networks, while social innovation depends more strongly on internal capabilities such as workforce skills and organisational practices. Third, although regional conditions shape innovation environments, firm-level capabilities play a dominant role.

Importantly, the combination of shared drivers and a negative conditional relationship between eco- and social innovation highlights the existence of capability trade-offs. Firms face constraints in allocating resources across different innovation domains, reinforcing the role of absorptive capacity and resource orchestration (Cohen and Levinthal, 1990; Teece, 2007).

These findings contribute to the literature by integrating eco-innovation and social innovation within a unified framework that links firm-level capabilities with multi-level contexts. They also suggest that sustainability-oriented innovation depends less on location itself than on firms' ability to absorb and reconfigure knowledge across competing domains.

The study has some limitations. The cross-sectional nature of the data does not allow for causal inference, and the measurement of social innovation remains imperfect. Future research could address these issues using longitudinal data and more refined indicators, as well as exploring sectoral and institutional differences in greater depth.

Overall, the results highlight that sustainability transitions require more than technological upgrading. They depend on firms' capacity to combine digital transformation with organisational change and capability development within diverse territorial contexts.

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Appendix A.

Table A.1 - Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Eco-innovation	1.000									
(2) Social innovation	0.217	1.000								
(3) i40	0.105	0.088	1.000							
(4) total_i40	0.168	0.134	0.761	1.000						
(5) Org_innov	0.153	0.151	0.089	0.129	1.000					
(6) Network	0.034	0.007	0.039	0.060	0.001	1.000				
(7) Skills	0.008	0.037	0.013	0.024	0.008	0.088	1.000			
(8) Fin_access	0.040	0.039	0.039	0.042	0.020	0.113	0.067	1.000		
(9) Log (employees)	0.121	0.064	0.104	0.155	0.078	0.054	0.071	0.082	1.000	
(10) Log (age)	0.046	0.013	0.042	0.056	-0.009	0.043	0.009	0.050	0.201	1.000

Table A2 - Variance Inflation Factors (VIF)

	VIF	1/VIF
Log (employees)	1.06	.944
Log (age)	1.045	.957
Fin_access	1.022	.978
Network	1.021	.979
Skills	1.015	.986
Org_innov	1.007	.993
Mean VIF	1.028	.

Table A.3 - Recursive biprobit model with social innovation as a determinant of eco-innovation

	(1) Eco-innovation	(2) Social Innovation
Social Innovation		-0.811*** (0.137)
i40	0.227*** (0.0330)	0.282*** (0.0299)
Org_innov	0.479*** (0.0343)	0.539*** (0.0360)
Network	-0.0105 (0.0124)	0.0238* (0.0125)
Skills	0.0430*** (0.0131)	0.0142 (0.0126)
Fin_access	0.0362*** (0.0117)	0.0333*** (0.0104)
Log (employees)	0.0377*** (0.00908)	0.0659*** (0.00890)
Log (age)	-0.00825 (0.0173)	0.0253* (0.0139)
Constant	-1.189*** (0.112)	-1.245*** (0.140)
Observations	13106	13,106
rho (ρ)	1.117*** (0.235)	
Wald test of rho = 0 (chi2)	22.5649	
Prob>chi2	0.0000	
Log likelihood	-12940	-12940
Wald chi2	1086	1086
Prob > chi2	0	0

Notes: Robust standard errors in parentheses*** p<0.01, ** p<0.05, * p<0.1

Table A.4 - Control Function Results for Social-Innovation

	(1)
	Social-Innovation (Dependent variable)
Eco-innovation	-1.970*
	(1.162)
uhat_eco	2.585**
	(1.162)
i40	0.374***
	(0.0881)
Org_innov	0.794***
	(0.182)
Network	0.00863
	(0.0162)
Skills	0.0435***
	(0.0133)
Fin_access	0.0518***
	(0.0146)
Log (employees)	0.0767***
	(0.0261)
Log (age)	0.0131
	(0.0210)
Constant	-1.218***
	(0.109)
Observations	13,106
Log likelihood	-6125
Wald chi2	616
Prob > chi2	0.0000

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Eco-innovation is treated as endogenous. The residual term (uhat_eco), obtained from the first-stage estimation, is included in the second-stage equation as a control function. The statistical significance of uhat_eco provides evidence of endogeneity

Table A.5 - Baseline probit estimates of eco-innovation and social innovation

	(1) Eco-innovation	(2) Eco-innovation	(3) Eco-innovation	(4) Social innovation	(5) Social innovation	(6) Social innovation
i40	0.288*** (0.0324)		0.261*** (0.0311)	0.253*** (0.0339)		0.226*** (0.0334)
Org_innov		0.491*** (0.0395)	0.470*** (0.0391)		0.488*** (0.0360)	0.470*** (0.0352)
Network	0.0329*** (0.0123)	0.0373*** (0.0123)	0.0343*** (0.0122)	-0.00970 (0.0123)	-0.00668 (0.0123)	-0.00915 (0.0123)
Skills	-0.000201 (0.0129)	-0.00126 (0.0132)	-0.000661 (0.0131)	0.0404*** (0.0130)	0.0402*** (0.0131)	0.0411*** (0.0133)
Fin_access	0.0271** (0.0107)	0.0287*** (0.0106)	0.0265** (0.0107)	0.0354*** (0.0115)	0.0372*** (0.0116)	0.0355*** (0.0116)
Log (employment)	0.0744*** (0.00923)	0.0730*** (0.00924)	0.0676*** (0.00895)	0.0420*** (0.00956)	0.0395*** (0.00942)	0.0347*** (0.00925)
Log (age)	0.0296** (0.0143)	0.0382*** (0.0140)	0.0348** (0.0141)	-0.00938 (0.0173)	-0.00135 (0.0174)	-0.00468 (0.0175)
1.dnace_a1	0.0686 (0.230)	0.140 (0.231)	0.157 (0.233)	-0.712** (0.309)	-0.642** (0.307)	-0.627** (0.306)
1.dnace_a2	0.251*** (0.0966)	0.255*** (0.0960)	0.250*** (0.0954)	-0.143 (0.0872)	-0.146 (0.0890)	-0.150* (0.0889)
1.dnace_a3	0.471*** (0.137)	0.541*** (0.139)	0.516*** (0.138)	-0.492*** (0.167)	-0.436*** (0.167)	-0.462*** (0.167)
1.dnace_a4	0.512*** (0.123)	0.507*** (0.122)	0.516*** (0.121)	-0.153 (0.125)	-0.170 (0.126)	-0.160 (0.127)
1.dnace_a5	0.0990 (0.0926)	0.0938 (0.0926)	0.102 (0.0923)	-0.259*** (0.0874)	-0.272*** (0.0882)	-0.264*** (0.0885)
1.dnace_a6	0.107 (0.0865)	0.110 (0.0865)	0.106 (0.0862)	-0.191** (0.0867)	-0.191** (0.0880)	-0.195** (0.0880)
1.dnace_a7	0.175* (0.0932)	0.183** (0.0923)	0.192** (0.0925)	-0.294*** (0.0965)	-0.290*** (0.0973)	-0.286*** (0.0974)
1.dnace_a8	0.188** (0.0943)	0.180* (0.0943)	0.186** (0.0940)	-0.0959 (0.0919)	-0.111 (0.0932)	-0.106 (0.0934)
1.dnace_a9	0.0398 (0.0943)	0.0438 (0.0963)	0.0188 (0.0955)	-0.0456 (0.106)	-0.0421 (0.108)	-0.0676 (0.107)
1.dnace_a10	0.130 (0.100)	0.127 (0.100)	0.127 (0.101)	-0.200* (0.103)	-0.214** (0.103)	-0.214** (0.103)
1.dnace_a11	0.134 (0.127)	0.137 (0.127)	0.139 (0.128)	-0.229* (0.135)	-0.232* (0.138)	-0.225 (0.139)
1.dnace_a12	0.00494 (0.0910)	0.0262 (0.0917)	-0.000589 (0.0911)	-0.0927 (0.0899)	-0.0775 (0.0908)	-0.101 (0.0910)
1.dnace_a13	0.0252 (0.0974)	0.00906 (0.0961)	0.00883 (0.0952)	-0.0910 (0.0960)	-0.112 (0.0978)	-0.111 (0.0976)
1.dnace_a14	-0.0267 (0.100)	0.000534 (0.0997)	-0.0129 (0.0998)	0.0447 (0.0939)	0.0688 (0.0946)	0.0600 (0.0941)
1.dnace_a15	-0.0185 (0.103)	-0.0194 (0.103)	-0.0247 (0.103)	0.180* (0.0947)	0.182* (0.0971)	0.180* (0.0972)
Constant	-1.489*** (0.118)	-1.420*** (0.115)	-1.557*** (0.117)	-1.122*** (0.111)	-1.068*** (0.110)	-1.187*** (0.112)
Observations	13,106	13,106	13,106	13,106	13,106	13,106
Log likelihood	-6931	-6865	-6819	-6463	-6387	-6355
LR chi2	207.3	333.6	376.9	182.7	314.1	339.9
Prob > chi2	0	0	0	0	0	0
Pseudo R2	0.0274	0.0367	0.0431	0.0206	0.0322	0.0371
N	13106	13106	13106	13106	13106	13106

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sector and NUTS2 regional fixed effects are included in all specifications.