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Co-Creation Over R&D: External Knowledge as the Engine of Green Innovation in Italian SMEs

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ABSTRACT

The transition towards a green and net-zero economy has become a strategic priority for firms and policymakers, placing increasing pressure on SMEs to integrate diverse forms of knowledge to achieve both environmental and economic objectives. A recurring yet not fully resolved question is whether co-creation among demand- and supply-side actors is associated with firms' environmental performance while also contributing to firm-level economic outcomes. Drawing on survey data from 6646 Italian firms, this paper investigates the associations between co-creation, digital technologies, government support, and green innovation. Using a CDM-inspired two-stage econometric framework, we find that co-creation and external enablers are strongly associated with green innovation. Green innovation is also positively associated with firm performance, suggesting that environmentally oriented innovation may be linked to economic benefits for SMEs. Moreover, our results indicate that internal R&D intensity has no significant direct association with green innovation among SMEs. These findings suggest that SMEs often rely on a network-intensive model of green innovation, in which external collaborations play a central role, while internal R&D intensity becomes complementary only as firms develop greater organizational capacity.

1 | Introduction

Pressures from regulators, markets, and society are increasingly pushing firms to adopt greener production and align with the transition toward a net-zero economy (Hermundsdottir and Aspelund 2021; Vasileiou et al. 2022). Green innovation, widely understood as innovations that reduce environmental harm or generate positive environmental outcomes, has therefore become a central element of contemporary industrial transformation (Vasileiou et al. 2022; Block et al. 2025). Achieving this transformation typically involves the development of new knowledge, technologies, and organizational practices that support environmentally sustainable production (Xie et al. 2019). While large corporations often rely on structured research and development (R&D) systems to address sustainability challenges, small and medium-sized enterprises (SMEs) typically face different constraints, operating with limited financial and technological resources. This raises an important but insufficiently understood question: *how do SMEs develop green innovation when internal R&D capabilities are limited, and what role does external knowledge play in enabling such innovation?*

Traditional innovation theories suggest that internal R&D capabilities enhance firms' ability to absorb and exploit external knowledge, thereby supporting innovation outcomes (Cohen and Levinthal 1990; Zahra and George 2002). However, many SMEs lack formal R&D infrastructure yet still manage to introduce environmentally oriented innovations (Vega-Jurado et al. 2008; Antonelli et al. 2013). Instead, firms often rely on knowledge obtained through interactions with customers, suppliers, and other external partners (Oksanen and Hautamäki 2015; De Silva et al. 2018). Such interactions can provide firms with access to complementary knowledge distributed across markets and value chains (Chesbrough 2025).

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These patterns suggest that network-based knowledge creation may partially substitute for, or complement, internal R&D in enabling green innovation among resource-constrained firms, a possibility that remains insufficiently explored in the literature.

Building on this logic, innovation increasingly emerges through collaboration and knowledge exchange among multiple actors. Prior studies highlight that firms co-create value by integrating knowledge from stakeholders across demand- and supply-side relationships (Frow et al. 2015; Payne et al. 2008). In this study, co-creation is conceptualized as firms' deliberate engagement with external actors to integrate complementary knowledge into innovation processes. Specifically, we examine four external knowledge channels: (1) formal co-creation through partnerships and collaborative agreements, (2) customer knowledge co-creation through continuous interaction with customers, (3) supplier collaboration as a source of technical and process knowledge, and (4) market research as a structured mechanism for identifying emerging needs and opportunities.[1]

Understanding how these channels contribute to green innovation is particularly important because environmentally oriented knowledge is often distributed across value chains and institutional environments. Firms must interpret regulatory requirements, understand evolving customer preferences for sustainable products, and collaborate with suppliers to implement greener processes. Consequently, green innovation may depend not only on internal knowledge creation but also on firms' ability to integrate diverse external knowledge sources (Zhang et al. 2020). Recent technological developments further reshape these dynamics. Digital technologies such as the Internet of Things (IoT) and big data analytics enable firms to collect, process, and interpret large volumes of information from markets, supply chains, and production systems (de Camargo Fiorini et al. 2018; Ritala et al. 2024). In this sense, these digital technologies can be interpreted as knowledge-integration capabilities that strengthen firms' ability to transform distributed external knowledge into innovation outcomes.

These dynamics became particularly salient during and after the COVID-19 disruption. The pandemic exposed vulnerabilities in supply chains, intensified uncertainty, accelerated digital adoption, and increased firms' reliance on external partners for information, problem-solving, and resource access. Recent evidence suggests that collaborative relationships supported by digital technologies became increasingly important not only for innovation but also for organizational resilience and adaptation in turbulent environments (Vivaldini and de Sousa 2026). In this context, co-creation can be viewed not only as a mechanism associated with innovation but also as a means through which firms access complementary knowledge and capabilities needed to respond to environmental disruptions and sustainability challenges.

Despite growing attention to sustainable innovation, the mechanisms through which co-creation contributes to green innovation, particularly among SMEs, remain insufficiently understood. Existing research on corporate innovation continues to emphasize internal organizational capabilities and financial resources (Galende and de la Fuente 2003; Barman et al. 2022). Although several studies acknowledge the importance of external collaboration for innovation (Oksanen and Hautamäki 2015; De Silva et al. 2018), they typically treat external knowledge sources as a relatively homogeneous category. As a result, limited attention has been paid to whether knowledge originating from demand-side actors and knowledge originating from supply-side actors contribute differently to environmentally oriented innovation. This distinction is theoretically important because these actors provide different types of knowledge and incentives. Demand-side channels may help firms identify sustainability-related market needs, user preferences, and adoption barriers, whereas supply-side channels may provide technical, operational, and process-related knowledge necessary for implementing greener production practices. To the best of our knowledge, existing studies have rarely distinguished the roles of knowledge originating from demand-side and supply-side actors in shaping the development of environmentally oriented innovations. This study addresses this gap by examining how co-creation with external stakeholders is associated with firms' engagement in green innovation. We also consider the enabling roles of digital technologies and public policy instruments that support firms' transition toward sustainable production. By distinguishing between knowledge originating from demand-side actors (customers and market research) and supply-side actors (suppliers and formal partners), this study provides a more fine-grained understanding of how different external knowledge channels shape the development of green innovation among SMEs.

The Italian context provides a particularly relevant setting for examining these issues. Italy is characterized by a production system dominated by SMEs, many of which operate with limited formal R&D resources yet play a central role in industrial innovation and sustainability transitions. At the same time, substantial regional heterogeneity exists in terms of innovation capacity, knowledge networks, and firm performance, reflecting long-standing differences across Italian territories (Crescenzi et al. 2015; Aiello et al. 2024). Moreover, the period examined in this study spans the years surrounding the COVID-19 disruption and subsequent recovery, offering a context in which collaboration, digital transformation, and public support became increasingly important for firms seeking to maintain competitiveness while advancing sustainability objectives.

This study contributes to the literature on sustainable and open innovation in three ways. First, it contributes to open and sustainable innovation research by repositioning SMEs as network-embedded innovators whose green innovation activities emerge through interactions with multiple external actors rather than primarily through internal R&D investments. By distinguishing between demand-side actors (customers and market research) and supply-side actors (suppliers and formal partners), the study provides a more fine-grained understanding of how different external knowledge networks support environmentally oriented innovation. Second, the study highlights the role of digital technologies as knowledge-integration capabilities that enable firms to transform externally sourced information into green innovation outcomes. Third, the analysis refines the relationship between internal and external knowledge sources by examining the role of internal R&D intensity as a potential complement to or substitute for co-creation in SME innovation systems.

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The paper therefore addresses the following main research question: *How is co-creation with external actors—such as customers, suppliers, and partners—associated with firms' engagement in green innovation? To address this question, we further examine two related sub-questions: (1) How are enabling factors such as digital capabilities, government support, and internal R&D intensity associated with the development of green innovation? (2) Is participation in green innovation associated with improved firm performance?*

To answer these questions, we analyze survey data from 6646 Italian firms collected during 2019–2020. Using a Crépon–Duguet–Mairesse (CDM)-inspired two-stage econometric framework, we examine how external knowledge channels are associated with the adoption of different types of green innovation, including product innovation, process innovation, improvements in environmental characteristics, and circular economy initiatives. Our findings indicate that collaboration with customers, suppliers, and formal partners is positively associated with firms' engagement in green innovation.[2] Digital technologies and government support are also positively associated with firms' engagement in environmentally oriented innovation. Internal R&D intensity does not appear to have a direct association with green innovation among SMEs, suggesting that sustainable innovation in this context may be more closely associated with network-based knowledge exchange than with internal R&D activities. Furthermore, firms that engage in green innovation exhibit higher levels of productivity and revenue growth.

The remainder of the paper is structured as follows. Section 2 develops the theoretical background and hypotheses. Sections 3 and 4 describe the data and empirical methodology. Section 5 presents the empirical results. Section 6 discusses the findings and their implications. Section 7 concludes the paper and outlines policy implications. Section 8 discusses limitations and avenues for future research. Additional methodological details and robustness analyses are reported in the appendices.

2 | Theoretical Background and Hypotheses

This study builds on firm-level perspectives on open innovation and environmentally sustainable innovation, which view innovation as a distributed process in which firms purposefully source, combine, and apply knowledge across organizational boundaries to achieve economic and environmental outcomes (Chesbrough 2003; Laursen and Salter 2006; Janik and Ryszko 2025). In sustainability contexts, the relevant knowledge base is often dispersed across markets and value chains, including customer usage requirements, supplier technologies and materials, and evolving regulatory or certification expectations. As a result, green innovation in SMEs can be understood as a network-embedded process in which firms mobilize and integrate knowledge distributed across customers, suppliers, partners, and broader innovation ecosystems (Kimpimäki et al. 2022; Janik and Ryszko 2025).

Figure 1 summarizes our conceptual framework. We conceptualize co-creation as firms' deliberate engagement with external actors to integrate complementary knowledge into innovation

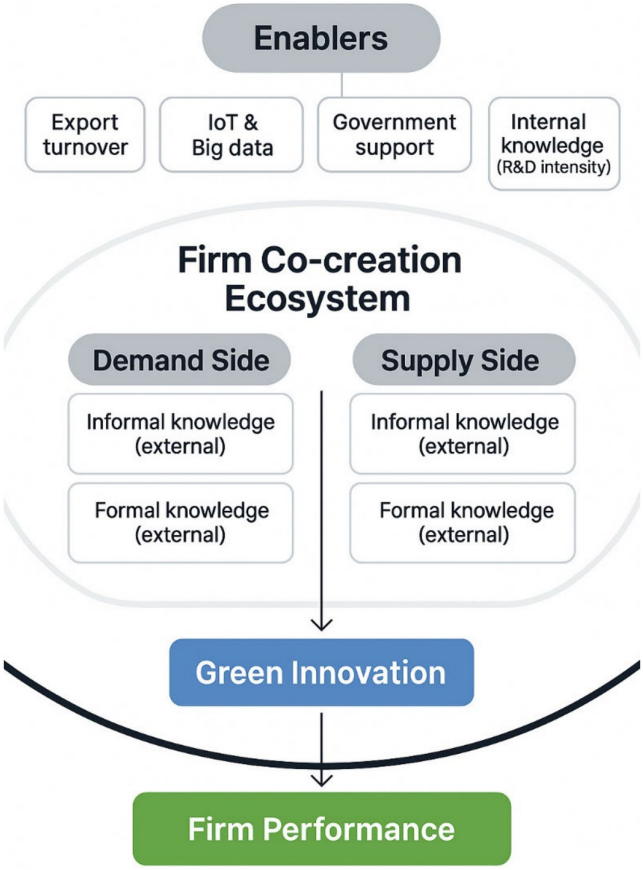


FIGURE 1 | Conceptual framework: Co-creation, green innovation, and firm performance. *Note:* This graphic representation illustrates the conceptual relationships among co-creation, green innovation, and firm performance, highlighting the study's main contributions.

processes (Payne et al. 2008; Frow et al. 2015). While related to broader concepts such as collaboration, inbound open innovation, external knowledge search, and absorptive capacity, co-creation is conceptually distinct. Collaboration refers to the relational interaction among actors, inbound open innovation concerns the purposeful sourcing and integration of external knowledge, external knowledge search captures activities aimed at identifying knowledge beyond firm boundaries, and absorptive capacity reflects the firm's ability to recognize, assimilate, and apply that knowledge (Cohen and Levinthal 1990; Zahra and George 2002; Chesbrough 2003; Laursen and Salter 2006). Recent research continues to emphasize the importance of these knowledge-related capabilities for sustainability-oriented innovation and interorganizational collaboration (Kimpimäki et al. 2022; Janik and Ryszko 2025). In this study, co-creation refers specifically to the interactive mechanisms through which firms engage external actors in the joint generation, integration, and application of knowledge for innovation purposes. While some channels, such as customer interaction, supplier collaboration, and formal partnerships, involve direct relational engagement with external actors, market research represents a more structured form of external knowledge search. We include both interactive and search-based mechanisms because they provide complementary pathways through which SMEs access, interpret, and integrate external knowledge into innovation activities. Nevertheless, we acknowledge that these channels differ

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in the degree of interaction involved. Consistent with open innovation research, we focus on firm-level inbound and coupled knowledge channels, some of which involve direct co-creation while others capture structured external knowledge search that is particularly salient for SMEs: (i) formal partnerships with external actors, (ii) continuous interaction with customers, (iii) collaboration with suppliers, and (iv) market research as systematic external search (Chesbrough 2003; Von Hippel 2005; Laursen and Salter 2006). These channels represent mechanisms through which firms access external knowledge and build absorptive capacity by recognizing, assimilating, and applying knowledge originating outside the firm (Cohen and Levinthal 1990; Zahra and George 2002). Recent research further highlights the importance of green absorptive capacity and interorganizational learning in translating external knowledge into sustainable performance outcomes through open innovation processes (Kim et al. 2025). Viewed from this perspective, SMEs are not merely users of external knowledge. Rather, they are network-embedded innovators that develop innovation capabilities through ongoing interactions with customers, suppliers, partners, and other actors in the innovation ecosystem. We examine how these channels relate to green innovation and, in turn, to firm performance. We also theorize the roles of digital technologies and public support as enabling conditions that shape firms' ability to convert external knowledge into green innovation outcomes (Lee et al. 2024; OECD 2025).

2.1 | Co-Creation as an External Knowledge Configuration for Green Innovation in SMEs

Co-creation has been discussed at the ecosystem level, involving diverse actors such as firms, universities, governments, intermediaries, and communities that integrate resources and knowledge towards innovation outcomes (De Silva et al. 2018, 2021, 2023). At the firm level, however, the central theoretical question is how firms mobilize co-creation relationships as knowledge inputs into innovation. Recent work emphasizes that environmentally sustainable innovation is particularly dependent on interorganizational knowledge integration because environmental problems and solutions cut across product life cycles and supply chains (Janik and Ryszko 2025; Kimpimäki et al. 2022). This logic is particularly relevant for SMEs, where innovation is often constrained by limited internal R&D capacity and specialized personnel.

In this study, we theorize co-creation as a multi-channel external knowledge configuration that supports green innovation through three mechanisms. First, external engagement increases knowledge variety by allowing SMEs to access specialized and complementary expertise that they cannot efficiently build internally. Second, co-creation reduces uncertainty by enabling firms to align innovation directions with customer acceptance, supplier feasibility, and implementation constraints. Third, co-creation supports implementation by facilitating coordination across demand-side requirements and supply-side capabilities, which is central to green products, greener processes, and circular economy initiatives.

We operationalize co-creation through four channels that capture demand- and supply-side knowledge flows. On the demand side, continuous customer interaction can reveal environmental preferences, performance expectations, and adoption barriers that shape the direction and design of green innovation (Rietveld and Schilling 2025; Prahalad and Ramaswamy 2004; Von Hippel 2005). In addition, market research provides structured external search, which may help SMEs recognize emerging sustainability requirements and competitive signals, including changing norms and compliance expectations (Dumitriu et al. 2019; Narver and Slater 1990; Kohli and Jaworski 1990). On the supply side, supplier collaboration enables joint problem-solving around material substitutions, energy efficiency, low-carbon logistics, and process redesign, which are central to eco-innovation implementation (Cai et al. 2026; Dyer and Singh 1998; De Marchi 2012). Recent research further suggests that sustainability and circular economy transitions depend heavily on engagement with key stakeholders, particularly customers and suppliers, who influence the adoption of environmental practices and the development of sustainability-oriented innovation (Provensi et al. 2026). Formal partnerships may also allow SMEs to access complementary technologies, share risks, and accelerate development by structuring the governance of knowledge exchange (Zhou and Baines 2024; Ragatz et al. 1997; Schiele 2010). We propose the following hypothesis:

Hypothesis 1. *Co-creation is positively associated with the likelihood that SMEs engage in green innovation.*

2.2 | Digital Technologies as a Knowledge-Integration Capability for Green Innovation

A persistent challenge in the co-creation and open innovation literature is that sourcing external knowledge does not automatically translate into innovation outcomes (West and Bogers 2014; Bashir and Alsaeed 2026). Firms must possess the capability to recognize, integrate, and apply diverse knowledge sources (Mubarak et al. 2025). Digital technologies may facilitate this translation by expanding firms' capacity to collect, process, and recombine data originating from markets and value chains. Internet of Things (IoT) technologies generate detailed operational and environmental information, for example regarding resource consumption, process efficiency, and traceability, while big data analytics supports decision-making across complex information streams (de Camargo Fiorini et al. 2018; Ritala et al. 2024). Beyond information processing, digital technologies can strengthen interorganizational coordination and knowledge exchange across supply chains. Industry 4.0 research increasingly highlights digitalization as a critical enabler of sustainability transformation because it improves visibility, integration, and coordination among actors while facilitating environmentally sustainable practices (Pandey et al. 2025).

Recent research increasingly treats digitalization not merely as a parallel antecedent but as a capability that supports knowledge integration and may amplify innovation outcomes in sustainability contexts. For example, evidence from technology and sustainability research links digital strategies and servitization to green innovation through mechanisms associated with absorptive capacity and capability transformation (Lee et al. 2024). Recent firm-level evidence further

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suggests that digital capabilities are positively associated with both green innovation and subsequent firm performance, highlighting the importance of organizational capabilities in translating digital technologies into sustainability-oriented outcomes (Shah et al. 2026). Related work on digital green value co-creation similarly emphasizes that digitally enabled co-creation behaviors and network embedding can improve green innovation performance (Yin and Zhao 2024). These arguments suggest that digital capabilities should be positively associated with green innovation because they may enhance firms' ability to integrate and apply externally sourced knowledge. We propose the following hypothesis:

Hypothesis 2. *Digital technologies (IoT and big data analytics) are positively associated with SMEs' engagement in green innovation.*

2.3 | Public Support as an Enabling Condition for SME Green Innovation

Green innovation is often characterized by higher uncertainty, longer payback horizons, and positive externalities that reduce private incentives compared with conventional innovation (Roper and Tapinos 2016; Yang and Jiang 2026). These features may be especially restrictive for SMEs, which face tighter financing constraints and thinner managerial bandwidth. Public policy instruments such as tax incentives, grants, and advisory support may help ease these constraints by reducing financial risk, supporting experimentation, and enabling investments in capability-building and collaboration (Horbach 2008).

Policy research and international evidence emphasize that effective SME greening often requires both financial and nonfinancial support, including programs that strengthen SMEs' capacity to develop, test, and commercialize sustainable solutions and to connect with collaborative innovation networks (OECD 2025). In addition, prior research suggests that external institutional pressures and policy-related incentives can encourage firms to pursue green innovation activities by reducing uncertainty and increasing incentives for environmental investments (Chen et al. 2018). Together, these arguments suggest that government support should be positively associated with firms' adoption of green innovation. We propose the following hypothesis:

Hypothesis 3. *Government support is positively associated with SMEs' engagement in green innovation.*

2.4 | Internal R&D Intensity and the Configuration of SME Green Innovation

Absorptive capacity theory emphasizes that internal knowledge development supports firms' ability to identify, assimilate, and exploit external knowledge (Cohen and Levinthal 1990; Zahra and George 2002; Abbas 2026). However, in SME contexts, internal R&D expenditures are often modest and may not map neatly onto formal innovation routines. A configuration perspective is therefore particularly relevant for SMEs, where internal R&D may operate primarily as a capability that facilitates firms' interaction with external knowledge sources rather than as the sole driver of innovation outputs.

Research on open innovation suggests that the relationship between openness and internal R&D is often complementary and context-dependent (Laursen and Salter 2006; Lu and Chesbrough 2022; Naqshbandi 2026). Internal R&D may strengthen firms' ability to recognize and integrate externally generated knowledge and may therefore be associated with greater benefits from collaborative innovation activities. Reviews of environmentally sustainable innovation similarly emphasize the need to better understand how internal and external knowledge mechanisms combine in sustainability-oriented innovation models (Janik and Ryszko 2025).

In the context of SMEs, internal R&D intensity may therefore play a dual role. On the one hand, it may contribute directly to the development of green innovation by supporting internal knowledge creation. On the other hand, it may function as an enabling capability that strengthens firms' ability to engage effectively in co-creation with external actors such as customers, suppliers, and partners. When internal R&D capabilities are stronger, firms may be better positioned to absorb and recombine externally sourced knowledge into environmentally oriented innovations. Based on this reasoning, we expect internal R&D to matter both directly and through its interaction with co-creation, although the relative strength of these effects may vary across SMEs. We propose the following hypotheses:

Hypothesis 4. *R&D intensity is positively associated with green innovation.*

Hypothesis 5. *The positive relationship between co-creation and green innovation is stronger when firms exhibit higher levels of R&D intensity.*

2.5 | Green Innovation and Firm Performance

Green innovation may contribute to firm performance through multiple channels. Environmentally improved products may be associated with greater differentiation and customer willingness to pay, greener processes may be associated with lower resource and compliance costs, and circular economy initiatives may be associated with higher material productivity and greater resilience in supply chains. At the same time, the literature recognizes variability in performance outcomes because green innovation may require up-front investments and coordination capabilities. Meta-analytic evidence shows that collaborative innovation is positively associated with innovation performance on average, while also highlighting that contextual conditions and institutional environments shape the strength of these relationships (Xie et al. 2023). In SME contexts, where co-creation and enabling conditions play a prominent role in innovation capability building, performance effects are expected to be reflected through green innovation outcomes rather than through co-creation alone. We propose the following hypothesis:

Hypothesis 6. *SMEs' engagement in green innovation is positively associated with firm performance, measured by revenue and productivity.*

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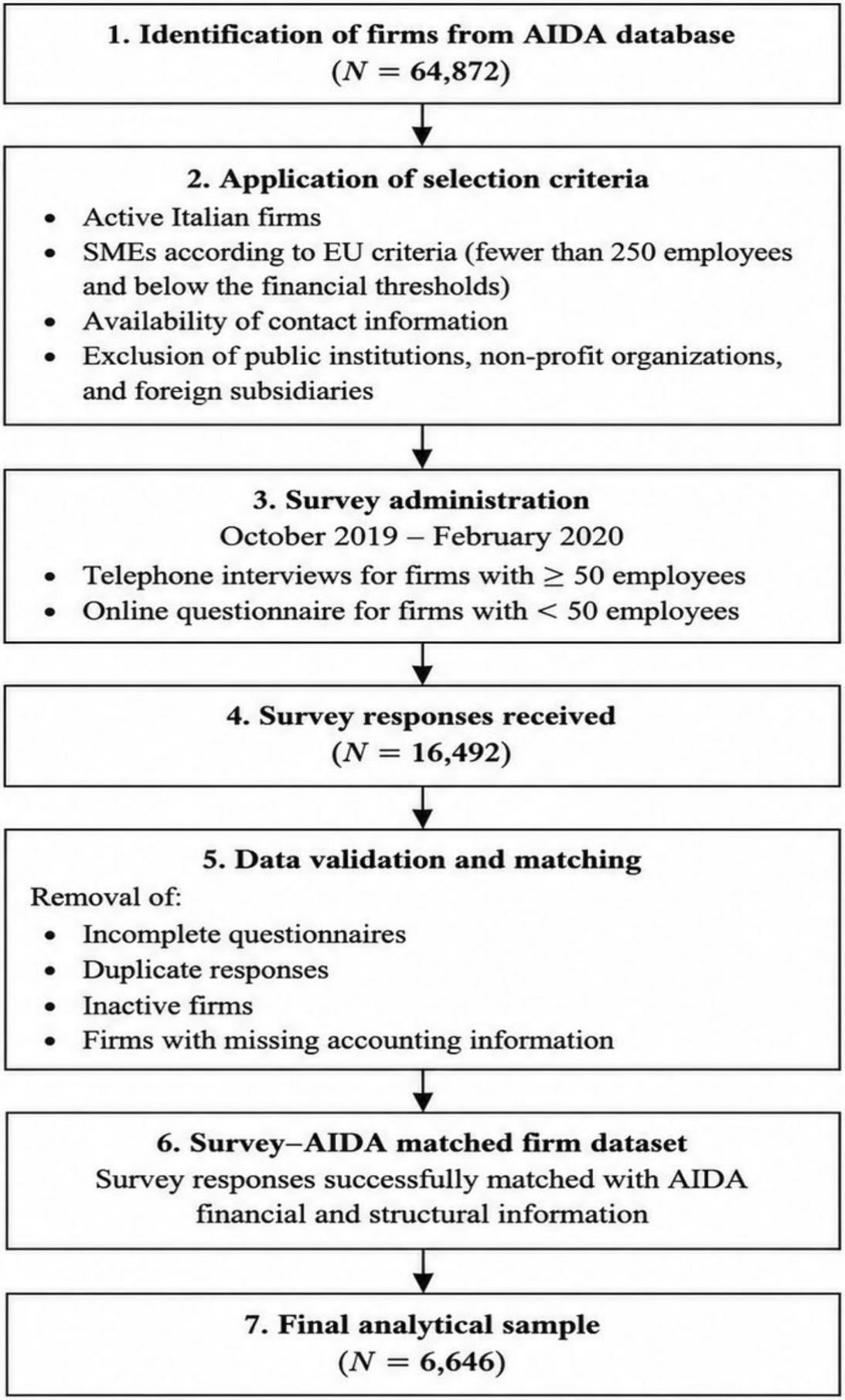


FIGURE 2 | Legend on next page.

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FIGURE 2 | Survey design and sample construction. *Note:* The figure summarizes the dataset construction process. Firms were initially identified from the Moody's Bureau van Dijk AIDA database and screened according to the study's selection criteria. The survey was administered between October 2019 and February 2020 using telephone interviews for firms with 50 or more employees and online questionnaires for firms with fewer than 50 employees. Survey responses were subsequently validated, matched with Moody's Bureau van Dijk AIDA financial information, and screened for incomplete questionnaires, duplicate responses, inactive firms, and missing accounting information. The final analytical sample consists of 6646 Italian SMEs. Although the original survey sampling frame included firms with fewer than 3000 employees, the final analytical sample used in this study consists exclusively of micro, small, and medium-sized enterprises (SMEs) with fewer than 250 employees.

3 | Research Design and Data

This study adopts a quantitative research design combining original survey data with administrative financial records. The research design proceeds in four stages. First, a structured survey was conducted to collect information on firms' collaboration activities, digital capabilities, and green innovation practices. Second, the survey responses were matched with financial and structural information obtained from the Moody's Bureau van Dijk AIDA database. Third, the combined dataset was cleaned and validated through representativeness checks and comparisons with national innovation statistics. Finally, the resulting firm-level dataset was used to estimate the relationships between co-creation, enabling capabilities, green innovation, and firm performance using a CDM-inspired two-stage econometric framework.

3.1 | Data Sources

Most existing empirical studies on innovation rely on data from large publicly listed firms, as financial and innovation information for these companies is more readily available. However, comprehensive firm-level information is often limited for privately held firms and SMEs. To address this gap, we conducted an original survey of Italian SMEs between October 2019 and February 2020.[3] Firms were identified using the Moody's Bureau van Dijk AIDA database, which provides detailed financial and structural information on Italian firms. Using this database, we constructed a sampling frame of 64,872 active micro, small, and medium-sized enterprises across multiple sectors of the Italian economy. The overall process used to construct the dataset is summarized in Figure 2.

The survey used a structured questionnaire directed at senior managers or firm owners responsible for strategic or innovation-related decisions. Firms were contacted via email and telephone, and responses were collected through structured interviews and online questionnaires. The questionnaire captured information on firms' co-creation practices, adoption of digital technologies, green innovation activities, and business model characteristics.[4] Table 1 reports the operationalization of all variables, while Appendix D provides the underlying survey items and coding procedures.

A total of 16,492 survey responses were received. The responses were subsequently validated and matched with accounting information from the Moody's Bureau van Dijk AIDA database. Observations were excluded when questionnaires were incomplete, duplicated, associated with inactive firms, or lacked the accounting information required for the empirical analysis. After these validation and matching procedures, the final analytical sample consisted of 6646 firms, corresponding to 10.24% of the original sampling frame.

To assess potential non-response bias, the characteristics of the responding firms were compared with those of the original population of 64,872 firms along three dimensions: firm size, firm age, and sector classification based on the NACE 3-digit industry code. In addition, the prevalence of green innovation in the sample was benchmarked against official national statistics from the Community Innovation Survey (CIS 2018). No statistically significant differences were observed between the sample and the population distributions, suggesting that the dataset provides a reasonably representative picture of innovation activity among Italian SMEs.

Financial and accounting information for the responding firms was retrieved from the Moody's Bureau van Dijk AIDA database and merged with the survey data using firm identifiers. This integration allowed us to construct a longitudinal dataset combining survey responses with objective financial performance indicators for the period 2020–2023. Because the performance period spans both the COVID-19 pandemic and the subsequent recovery phase, we conduct an additional sensitivity analysis distinguishing pandemic-period outcomes (2020–2021) from recovery-period outcomes (2022–2023). The results are reported in Appendix Table E5. Additional details on the sampling criteria, geographical distribution, and industry composition of the surveyed firms are reported in Appendix B.

3.2 | Variables

This section describes the definitions of key variables used in the empirical analysis, including the dependent variable and the main explanatory variables. Our empirical analysis relies on firm-level data from the 2019–2020 survey of Italian SMEs combined with financial information from the Moody's Bureau van Dijk AIDA database (2020–2023).

3.2.1 | Dependent Variable

The main dependent variable is green innovation, measured as a binary indicator equal to one if the firm reported introducing at least one of the following activities during the survey period: (i) green product innovation, (ii) green process innovation, (iii) improvements in the environmental characteristics of existing products, or (iv) circular economy-related projects, and zero otherwise. In additional analyses, these four dimensions are examined separately to explore potential heterogeneity across different forms of green innovation.

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TABLE 1 | Operationalization of variables.

Variable	Definition	Operationalization	Database	Methodological references
Green innovation	Dummy indicating whether a firm engaged in any green innovation activity	1 if firm developed green products, green processes, improved green characteristics, or initiated circular/green projects; 0 otherwise	Survey responses (2019–2020)	Chen and Xing (2025); Vasileiou et al. (2022)
Green product innovation	Development of new or significantly improved products with environmental benefits	1 if firm developed green products; 0 otherwise	Survey responses (2019–2020)	Andersén (2021); Khan, Dhir, et al. (2021)
Green process innovation	Implementation of new or significantly improved production processes with environmental benefits	1 if firm developed green production processes; 0 otherwise	Survey responses (2019–2020)	Xie et al. (2019); Khan, Kaur, et al. (2021)
Improved green characteristics	Enhancement of environmental features of existing products	1 if firm improved green product characteristics; 0 otherwise	Survey responses (2019–2020)	Le (2022); De Marchi (2012)
Green circular economy project	Projects related to the circular economy or green transition	1 if firm initiated circular/green projects; 0 otherwise	Survey responses (2019–2020)	Block et al. (2025); Kirchherr et al. (2017)
Formal co-creation	Formal collaboration with external actors on the supply side	1 if firm formalized partnerships with suppliers/competitors; 0 otherwise	Survey responses (2019–2020)	Ramaswamy and Ozcan (2018); Prahalad and Ramaswamy (2004)
Knowledge co-creation	Demand-side knowledge co-creation with customers	1 if firm engaged in continuous exchange of information with customers; 0 otherwise	Survey responses (2019–2020)	Abbate et al. (2019); Zhang et al. (2020)
Collaborative development	Informal knowledge exchange with suppliers	1 if firm obtained data/information from suppliers; 0 otherwise	Survey responses (2019–2020)	Giordani et al. (2018); Fu and Piplani (2004)
Market research	Demand-side informal knowledge acquisition from markets	1 if firm conducted market research; 0 otherwise	Survey responses (2019–2020)	Małecka et al. (2025); Nambisan and Zahra (2016)
R&D intensity	Firm's investment in internal knowledge creation	R&D expenditure per employee	AIDA (2020)	Ji et al. (2024); Lee et al. (2014)
Log value added per employee	Firm's economic value creation	Natural logarithm of value added per employee	AIDA (2020–2023)	Conti et al. (2024); Croce et al. (2013)
Log revenue per employee	Firm's market performance	Natural logarithm of revenue per employee	AIDA (2020–2023)	Babina et al. (2024); Moretti and Biancardi (2020)
Log capital	Firm's capital stock	Natural logarithm of total capital stock	AIDA (2020)	Babina et al. (2024); Buesa et al. (2010)

(Continues)

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TABLE 1 | (Continued)

Variable	Definition	Operationalization	Database	Methodological references
Export turnover	Firm's international competitiveness	Share of revenue generated through exports (%)	Survey responses (2019–2020)	Najafi-Tavani et al. (2025)
IoT and big data	Adoption of digital technologies for monitoring and analytics	1 if firm adopted IoT or big data technologies; 0 otherwise	Survey responses (2019–2020)	Clarysse et al. (2022); Cappa et al. (2021)
Government support	Financial/policy incentives for innovation	1 if firm received government incentives or tax breaks; 0 otherwise	Survey responses (2019–2020)	Zuo and Lin (2022)
Firm size	Number of employees (proxy for resources/absorptive capacity)	Logarithm of total employees	AIDA (2020)	Haar et al. (2022); Acs and Audretsch (1988)
Firm age	Years since firm's founding (proxy for experience)	Logarithm of firm age	AIDA (2020)	Coad et al. (2016); Coad et al. (2013)

Note: Green innovation variables and co-creation measures are derived from the original SME survey conducted in Italy during 2019–2020. Financial and firm-level characteristics are obtained from the Moody's Bureau van Dijk AIDA database. Binary variables take a value of 1 when the specified activity or condition is present and 0 otherwise. The co-creation index is constructed from four external knowledge channels: formal co-creation, knowledge co-creation, collaborative development, and market research. Market research is treated as a structured external knowledge-search mechanism, while the other three channels involve more direct relational engagement with external actors.

3.2.2 | Independent Variables

The main explanatory variable is the co-creation index, which captures the extent to which firms engage with external actors in innovation-related activities. The index is constructed from four binary indicators representing four key collaboration channels: formal partnerships with external organizations, knowledge co-creation through customer interaction, collaborative development with suppliers, and market research activities. To ensure robustness, we construct the index using two approaches. First, we generate an equal-weighted composite index based on the four indicators. Second, we apply principal component analysis (PCA) to derive a data-driven index. Both approaches produce consistent results.

Digital technologies are measured using survey-based indicators capturing firms' adoption of Internet of Things (IoT) technologies and big data analytics. These technologies reflect firms' ability to collect, process, and utilize data to support operational and strategic decision-making. Government support is measured through firms' reported use of public support instruments aimed at facilitating innovation and business development. Detailed variable definitions and coding procedures are reported in Table 1 and Appendix Table D1. Recent evidence further suggests that big data analytics capabilities can support sustainability outcomes by helping firms process complex information, coordinate activities across organizational boundaries, and improve environmentally oriented decision-making (Rahman et al. 2026). From this perspective, big data analytics is not only a technological tool but also a capability that enables firms to transform data into sustainability-oriented actions and innovation outcomes.

All variables are summarized in Table 1, which provides detailed definitions, operationalizations, and references to the relevant methodological literature.

3.3 | Summary Statistics

We test our hypotheses using the dataset of 6646 Italian SMEs surveyed during 2019–2020. The dataset combines information from the survey with financial and structural data obtained from the Moody's Bureau van Dijk AIDA database. This integration enables the analysis of firms' collaboration activities, digital capabilities, green innovation activities, and financial performance within a unified empirical framework. Table 2 presents summary statistics for the variables used in the analysis.

3.4 | Descriptive Statistics

Table 3 reports the distribution of different types of green innovation by firm size.[5] Approximately 32% of firms reported engaging in at least one type of green innovation. Within this group, micro firms accounted for 48.5% and small firms for 40.3%, making them the largest contributors. Medium firms represented only 11.2% of green innovators, underscoring the SME-driven nature of green innovation in the Italian context. This pattern is particularly evident in green circular economy projects and improvements in green characteristics, which are reported more frequently than product or process innovations across all firm sizes.

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TABLE 2 | Summary statistics.

No.	Variable	Observations	Mean	Std. dev.	Minimum	Maximum
1	Green innovation	6646	0.316	0.465	0	1
2	Green product innovation	6646	0.077	0.268	0	1
3	Green process innovation	6646	0.094	0.293	0	1
4	Improved green characteristics	6646	0.169	0.375	0	1
5	Green circular economy project	6646	0.105	0.307	0	1
6	Formal co-creation	6646	0.369	0.482	0	1
7	Knowledge co-creation	6646	0.525	0.499	0	1
8	Collaborative development	6646	0.293	0.455	0	1
9	Market research	6646	0.206	0.404	0	1
10	R&D intensity	6646	0.640	8.055	0	293.5
11	Log value added per employee	6131	5.912	1.660	0	11.98
12	Log revenue per employee	6392	6.932	1.659	0	13.60
13	Log capital	6359	3.676	1.693	0	12.36
14	Export turnover	6646	15.44	26.49	0	100
15	IoT and big data	6646	0.090	0.286	0	1
16	Government support	6646	0.227	0.419	0	1
17	Firm size (employees)	6646	17.29	28.85	0	247
18	Firm age (years)	6646	20.16	14.25	2	120

Note: Summary statistics are reported for the variables used in the empirical analysis. Firm size and firm age are presented in their original units (employees and years) for ease of interpretation, although logarithmic transformations are used in the regression models where indicated. Differences in the number of observations reflect missing values across variables, primarily due to the availability of accounting information in the Moody's Bureau van Dijk AIDA database.

TABLE 3 | Distribution of green innovation by firm size. Distribution of green innovation types across firm-size categories ($N = 6646$).

	Green innovation		Green product innovation		Green process innovation		Improved green characteristics		Green circular economy projects	
Share of firms	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
All firms	2100	(31.6%)	513	(24.4%)	623	(29.6%)	1114	(53.0%)	698	(33.2%)
Micro firms	1018	(48.5%)	259	(50.4%)	282	(45.3%)	522	(46.9%)	343	(49.1%)
Small firms	846	(40.3%)	194	(37.8%)	256	(41.1%)	454	(40.8%)	261	(37.4%)
Medium firms	236	(11.2%)	60	(11.7%)	85	(13.6%)	138	(12.4%)	94	(13.5%)

Note: Percentages in parentheses indicate the share of each firm-size category within each innovation type. Firm-size categories follow the European Commission SME classification: micro firms (0–9 employees), small firms (10–49 employees), and medium-sized firms (50–249 employees).

Table 4 presents pairwise correlations among the key variables and variance inflation factors (VIFs). Types of green innovation (product, process, improved characteristics, and circular projects) are positively correlated with the overall green innovation variable, but none exhibit excessively high correlations (all < 0.7), suggesting that they capture distinct dimensions of sustainable innovation. Similarly, co-creation measures are interrelated but not collinear, reflecting different external knowledge channels.

Notably, R&D intensity shows very low correlations with green innovation and co-creation indicators, suggesting that internal R&D intensity is only weakly associated with green innovation in the sample. All explanatory variables have VIF values below 3.5, indicating no serious multicollinearity issues.

3.5 | Green Innovation in Italian Regions

Table 5 shows the frequency of green and non-green innovation across Italy's 20 regions. The regional distribution of green innovation is highly uneven: Lombardia, Veneto, and

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TABLE 4 | Correlation matrix and variance inflation factors.

No.	Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	VIF	1/VIF
(1)	Green innovation	1.00																			
(2)	Green product innovation	0.41	1.00																	1.14	0.87
(3)	Green process innovation	0.48	0.27	1.00																1.16	0.86
(4)	Improved green characteristics	0.66	0.18	0.21	1.00															1.12	0.89
(5)	Green circular economy project	0.49	0.16	0.20	0.11	1.00														1.09	0.91
(6)	Formal co-creation	0.17	0.10	0.11	0.11	0.12	1.00													1.14	0.87
(7)	Knowledge co-creation	0.24	0.08	0.11	0.18	0.12	0.22	1.00												1.27	0.78
(8)	Collaborative development	0.18	0.10	0.10	0.15	0.10	0.14	0.39	1.00											1.22	0.81
(9)	Market research	0.18	0.15	0.12	0.13	0.14	0.19	0.19	0.20	1.00										1.13	0.88
(10)	R&D intensity	0.01	0.01	0.00	0.02	0.00	0.03	−0.00	0.01	0.02	1.00									1.01	0.98
(11)	Log value added per employee	0.11	0.03	0.07	0.09	0.07	0.01	0.05	0.07	0.04	−0.02	1.00								1.63	0.61
(12)	Log revenue per employee	0.12	0.06	0.07	0.11	0.08	0.01	0.05	0.12	0.06	−0.02	0.88	1.00							1.70	0.58
(13)	Log capital	0.11	0.08	0.08	0.09	0.08	0.00	0.02	0.07	0.05	0.03	0.58	0.61	1.00						1.55	0.64
(14)	Export turnover	0.12	0.08	0.04	0.10	0.06	0.04	0.06	0.05	0.09	0.01	0.18	0.23	0.19	1.00					1.06	0.93
(15)	IoT and big data	0.08	0.08	0.09	0.03	0.06	0.18	0.11	0.04	0.10	0.07	0.02	−0.01	0.01	0.00	1.00				1.07	0.93
(16)	Government support	0.17	0.09	0.13	0.14	0.10	0.12	0.13	0.11	0.10	0.03	0.21	0.18	0.13	0.10	0.11	1.00			1.11	0.90
(17)	Firm size	0.10	0.02	0.06	0.09	0.07	0.01	0.03	0.07	0.04	−0.02	0.86	0.78	0.54	0.17	0.01	0.19	1.00		1.51	0.66
(18)	Firm age	0.05	0.00	0.03	0.03	0.01	−0.11	0.01	0.05	−0.06	−0.04	0.39	0.40	0.41	0.10	−0.10	0.09	0.36	1.00	1.30	0.76

Note: Pairwise Pearson correlation coefficients are reported below the diagonal. Variance inflation factors (VIFs) are reported in the final two columns to assess potential multicollinearity among explanatory variables. All VIF values are substantially below the commonly used threshold of 10, indicating that multicollinearity is unlikely to affect the regression estimates.

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Emilia-Romagna account for large absolute numbers of green innovators, while the regional shares also reveal substantial territorial variation.

Notably, some regions—such as Marche—contribute disproportionately more to green innovation relative to their share of non-green innovation, suggesting region-specific enabling conditions for sustainability-oriented transformation.

Figure 3 illustrates the geographical distribution of green innovation across Italian provinces, measured as the percentage of firms reporting green innovation within each province. It also highlights regional differences in engagement in green innovation.

Regions with high levels of green innovation, such as Lombardia, Veneto, and Emilia-Romagna, may benefit from agglomeration effects, whereby firms learn from one another within the innovation ecosystem. Overall, innovation activity—both green and non-green—is higher in northern Italy compared with southern regions.

3.6 | Green Innovation in Different Industries

Figure 4 presents the share of firms engaged in green and non-green innovation across 17 industries. The chemicals and pharmaceuticals sector exhibits the highest proportion of green innovation, followed by utilities (electricity, water, waste) and the agriculture, forestry, fishing, and wood, paper, printing, and furniture sectors. These industries are among the most prominent contributors to green innovation in Italy.

Other resource-intensive industries, such as rubber, plastics, non-metallic minerals, and metals, also demonstrate high levels of green innovation, potentially associated with regulatory pressures. At the same time, the presence of green innovation in information-intensive sectors indicates that green innovation is not confined to manufacturing; non-manufacturing industries are also actively engaged.

Traditional or resource-based sectors, such as mining and quarrying, report significant green innovation activity

TABLE 5 | Regional distribution of green innovation.

	Green innovation			Non-green innovation			Overall
Region	**Frequency**	**Percent**	**Cumulative**	**Frequency**	**Percent**	**Cumulative**	**Total firms**
Abruzzo	48	2.29	2.29	100	2.20	2.20	148
Basilicata	15	0.71	3.00	29	0.64	2.84	44
Calabria	21	1.00	4.00	38	0.84	3.67	59
Campania	85	4.05	8.05	182	4.00	7.68	267
Emilia-Romagna	212	10.10	18.14	515	11.33	19.01	727
Friuli-Venezia Giulia	68	3.24	21.38	133	2.93	21.93	201
Lazio	157	7.48	28.86	323	7.11	29.04	480
Liguria	26	1.24	30.10	78	1.72	30.75	104
Lombardia	476	22.67	52.76	1075	23.65	54.40	1551
Marche	179	8.52	61.29	311	6.84	61.24	490
Molise	5	0.24	61.52	14	0.31	61.55	19
Piemonte	140	6.67	68.19	297	6.53	68.08	437
Puglia	74	3.52	71.71	170	3.74	71.82	244
Sardegna	26	1.24	72.95	64	1.41	73.23	90
Sicilia	50	2.38	75.33	108	2.38	75.60	158
Toscana	148	7.05	82.38	297	6.53	82.14	445
Trentino-Alto Adige	68	3.24	85.62	145	3.19	85.33	213
Umbria	29	1.38	87.00	63	1.39	86.71	92
Valle d'Aosta	7	0.33	87.33	7	0.15	86.87	14
Veneto	266	12.67	100.00	597	13.13	100.00	863
Total	2100	100.00	100.00	4546	100.00	100.00	6646

Note: The table reports the geographical distribution of firms engaging and not engaging in green innovation across Italian NUTS-2 regions. Percentages are calculated within the green innovation and non-green innovation groups, respectively. The final column reports the total number of firms in each region included in the sample.

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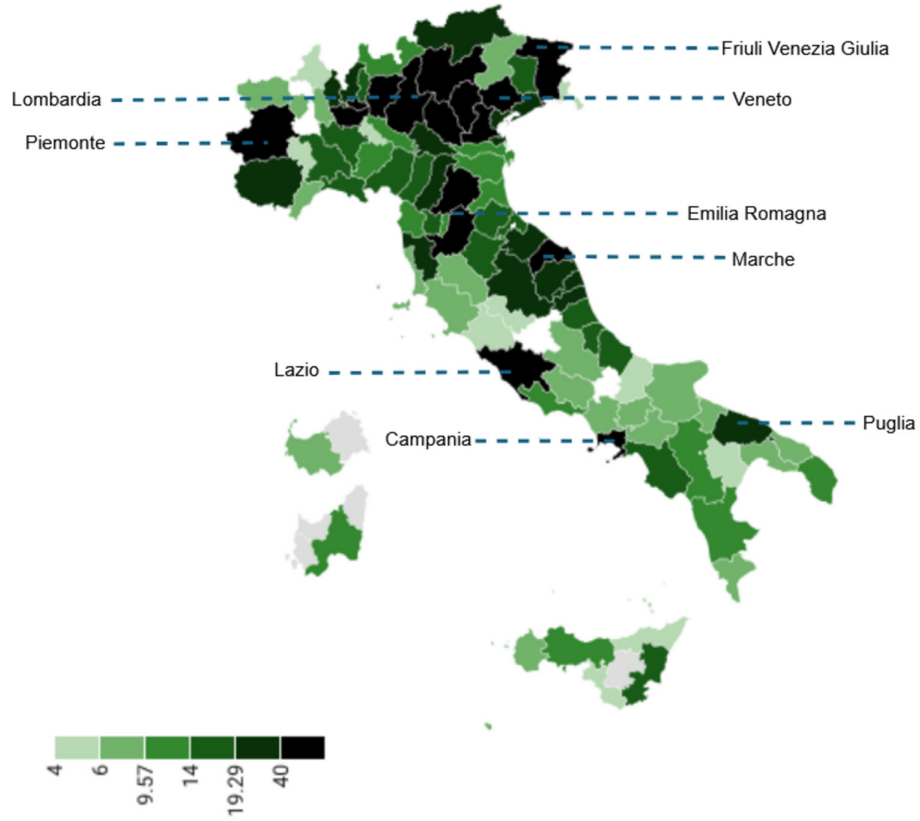


FIGURE 3 | Firms engaged in green innovation across Italian provinces. *Note:* Darker shades indicate a higher share of firms reporting green innovation.

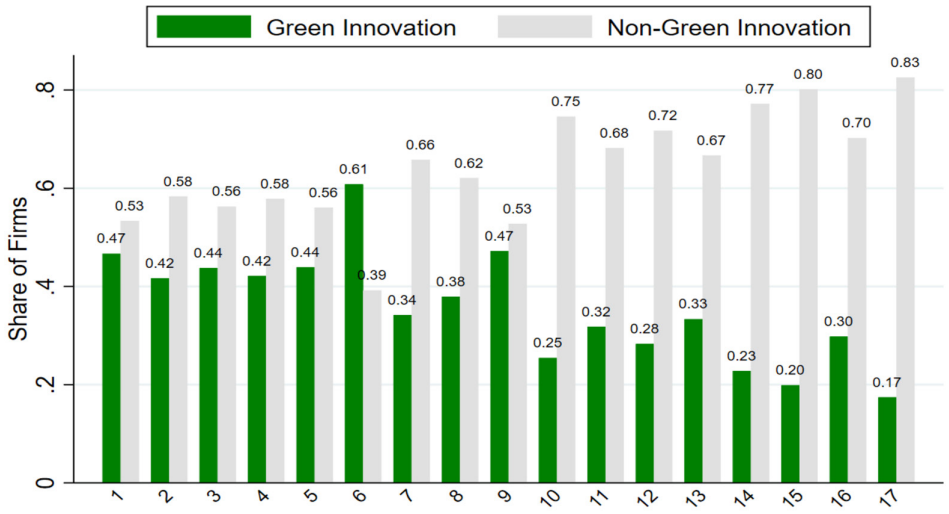


FIGURE 4 | Share of green and non-green innovation across industries. *Note:* Industry classification (1 to 17) corresponds to the following sectors: 1—Agriculture, Forestry, Fishing; 2—Mining and Quarrying; 3—Food, Beverages, Tobacco; 4—Textiles, Apparel, Leather; 5—Wood, Paper, Printing, Furniture; 6—Chemicals, Pharmaceuticals; 7—Rubber, Plastics, Non-Metallic Minerals, Metals; 8—Electronics, Electrical, Machinery, 9—Utilities (Electricity, Water, Waste); Vehicles; 10—Construction; 11—Wholesale, Retail, Vehicle Trade; 12—Transport, Storage, Postal; 13—Accommodation, Food Services; 14—Publishing, Media, Telecom, IT; 15—Finance, Insurance, Real Estate, Auxiliary; 16—Professional, Scientific, Technical, Admin; 17—Education, Health, Arts, Other Services.

as well. By contrast, industries such as education, health, arts, other services, and finance, insurance, real estate, and auxiliary services exhibit only moderate levels of green innovation.

4 | Methodology

In the literature on innovation and firm performance, two main econometric challenges are commonly discussed: selection bias

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and simultaneity bias. Selection bias arises because not all firms engage in innovation, and various factors influence a firm's decision to innovate—factors that may also affect firm performance (Hashi and Stojčić 2013).

To address these issues, prior studies (Wadho and Chaudhry 2018, 2024; Hall 2011) have employed multi-stage models. These models first identify the determinants of a firm's decision to innovate and then examine the relationship between innovation and performance outcomes.

Following this line of work, we adopt a CDM-inspired two-stage econometric framework, which reflects the sequential nature of innovation and reduces concerns regarding simultaneity and reverse causality, although it does not eliminate them entirely. The empirical model is estimated using a two-stage approach consistent with the CDM innovation framework, which captures the sequential relationship between innovation inputs, innovation outputs, and firm performance. Specifically, we estimate models of firms' propensity to introduce different forms of green innovation—green product innovation, green process innovation, improvements in the environmental characteristics of products, and green circular economy projects—and models of the relationship between green innovation and firm performance, measured by value added per employee and revenue per employee.

Our approach builds on the well-established CDM framework (Crépon et al. 1998).[6] In this framework, the first stage models the determinants of innovation outcomes based on observed firm-level characteristics that are plausibly exogenous, while the second stage uses predicted values from the first stage to estimate the relationship with performance outcomes. This procedure helps mitigate concerns related to endogeneity, including reverse causality between innovation and performance, as well as measurement error in innovation variables.

We specify the following equations:

$$\begin{aligned} \textit{Green Innovation}_i = {} & \beta_0 + \beta_1\, \textit{Co-creation Index}_i + \beta_2 \textit{R\&D Intensity}_i \\ & + \beta_3 \textit{Export turnover}_i + \beta_4 \textit{IoT\&Big data}_i \\ & + \beta_5 \textit{Government support}_i + \beta_6 \textit{Firm size}_i \\ & + \beta_7 \textit{Firm size}^2{}_i + \beta_8 \textit{Firm age}_i + \partial \textit{Industry FE}_{ji} \\ & + \gamma \textit{Region FE}_{ri} + \varepsilon_i \end{aligned} \tag{1}$$

$$\begin{aligned} \textit{Firm Performance}\ (Y)_i = {} & \beta_0 + \beta_1 \textit{Predicted Green Innovation}_i \\ & + \beta_2 \textit{Firm Capital}_i + \beta_3 \textit{Firm size}_i \\ & + \partial \textit{Industry FE}_{ji} + \gamma \textit{Region FE}_{ri} + \varepsilon_i \end{aligned} \tag{2}$$

Equation (1) is estimated using a probit model, where the baseline specification relates the co-creation index to green innovation (Model 1). A probit specification is appropriate because the dependent variable captures the binary occurrence of green innovation activities. The probit model estimates the probability that a firm engages in green innovation conditional on firm characteristics and external knowledge inputs. This approach is widely used in empirical innovation studies where the outcome variable reflects the adoption or introduction of innovation rather than continuous innovation intensity. The probit model generates predicted values of green innovation, which are then used in Equation (2) to estimate firm performance (Model 2). Using predicted rather than observed values is intended to reduce potential endogeneity concerns in the relationship between green innovation outputs and firm performance.

We assign equal weights to the four co-creation actors when constructing the co-creation index, for both conceptual and methodological reasons. Conceptually, the open innovation and co-creation literature suggests that different external knowledge sources—customers, suppliers, partners, and market research—are all considered important sources of innovation-related knowledge, and none can be considered inherently more important a priori (Prahalad and Ramaswamy 2004; Von Hippel 2005; Laursen and Salter 2006). Equal weighting reflects the theoretical view of complementarity, where each actor contributes unique yet comparable value to the innovation process.

Methodologically, equal weighting offers a transparent approach, particularly in the absence of strong theoretical or empirical justification for assigning differential weights. This approach avoids introducing arbitrary weighting that could privilege one actor over another. To validate this approach, we also constructed an alternative index using PCA, with details reported in Appendix C. The PCA-derived index produced results consistent with the equal-weighted index, supporting the robustness of our measure. Although the CDM framework helps reduce potential endogeneity concerns by modeling the sequential relationship between innovation and performance, we acknowledge that observational firm-level data cannot fully eliminate all sources of endogeneity. In particular, unobserved managerial capabilities or strategic orientation may be associated with both collaboration behavior and innovation outcomes. To mitigate these concerns, the empirical specification includes a rich set of firm-level controls together with industry and regional fixed effects, which capture unobserved heterogeneity across sectors and locations. In addition, the use of predicted innovation values in the second-stage equation helps reduce simultaneity between innovation outcomes and firm performance. Moreover, all empirical analyses were conducted using Stata/MP 19.5 (StataCorp, College Station, TX, United States), including the estimation of probit models, average marginal effects, ordinary least squares regressions, PCA, and robustness tests.

5 | Results

We first report the first-stage estimates examining the determinants of firms' engagement in green innovation. We then present the second-stage results linking predicted green innovation outcomes to firm performance. Finally, we report additional analyses on the interaction between co-creation and internal R&D intensity and explore heterogeneity across firm sizes.

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TABLE 6 | First-stage estimates: Co-creation and green innovation (Average marginal effects).

Variables	(1) Green innovation	(2) Green product innovation	(3) Green process innovation	(4) Improved green characteristics	(5) Green circular economy project
Co-creation index	0.101***	0.031***	0.036***	0.061***	0.042***
	(0.004)	(0.003)	(0.003)	(0.004)	(0.003)
R&D intensity	0.001	0.000	−0.001	0.001	0.000
	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)
Export turnover	0.001***	0.000***	0.000	0.000**	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
IoT and big data	0.095***	0.055***	0.064***	0.032*	0.034***
	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)
Government support	0.090***	0.022***	0.048***	0.062***	0.037***
	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)
Firm size	−0.022*	−0.019**	−0.018**	−0.002	−0.014
	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)
Firm size^2	0.007***	0.003*	0.004***	0.002	0.005***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Firm age	0.005	−0.001	0.007	−0.002	−0.004
	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)
Industry FE	Yes	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes	Yes
Observations	6044	5863	5862	6026	5973
Pseudo R^2	0.131	0.129	0.112	0.106	0.105

Note: Average marginal effects (AMEs) from probit models are reported. The dependent variables are binary indicators capturing firms' engagement in different forms of green innovation. Industry and regional fixed effects are included in all specifications. Robust standard errors are reported in parentheses. Differences in the number of observations reflect missing values across dependent variables and covariates. AMEs can be interpreted as changes in the probability of engaging in the respective green innovation activity associated with a one-unit increase in the explanatory variable, holding other variables constant. For example, the AME of 0.101 for the co-creation index in Column (1) indicates that a one-unit increase in the co-creation index is associated with a 10.1 percentage-point increase in the probability of engaging in green innovation. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

5.1 | Co-Creation, Digital Technologies, and Government Support—First Stage Estimates

Table 6 reports the first-stage estimates of the empirical model (Columns 1–5), where the probability of engaging in different types of green innovation is modeled as a function of the co-creation index and other firm-level characteristics.

Across all five dependent variables, the co-creation index exhibits positive and statistically significant average marginal effects.[7] For overall green innovation, a one-unit increase in the co-creation index is associated with a 10.1 percentage-point increase in the probability of engaging in green innovation. The corresponding average marginal effects are 3.1 percentage points for green product innovation, 3.6 percentage points for green process innovation, 6.1 percentage points for improvements in green characteristics, and 4.2 percentage points for circular economy projects. These results indicate that co-creation is not only statistically significant but also economically meaningful in shaping sustainability-oriented innovation among SMEs.

Digital technologies and government support also show substantial associations. The adoption of IoT and big data technologies is associated with a 9.5 percentage-point higher probability of engaging in green innovation, while government support is associated with a 9.0 percentage-point increase. The magnitude of these associations is comparable with that of co-creation, highlighting the importance of both technological and institutional enabling conditions. By contrast, internal R&D intensity does not exhibit a statistically significant association with any green innovation outcome in the full sample.

The coefficients on firm size and firm size squared indicate a nonlinear relationship between firm size and green innovation.

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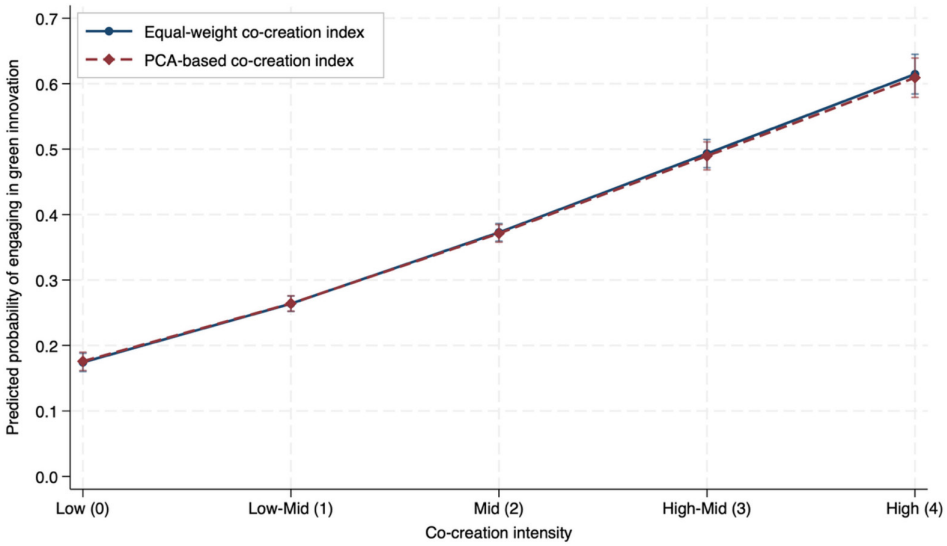


FIGURE 5 | Predicted probability of green innovation across levels of co-creation. *Note:* Predicted probabilities are obtained from probit models controlling for R&D intensity, export turnover, IoT and big data adoption, government support, firm size, firm age, industry fixed effects, and regional fixed effects. Error bars represent 95% confidence intervals.

To facilitate interpretation, Appendix Table E4 reports the estimated turning points implied by the quadratic specification. The estimated thresholds range from approximately 2 to 23 employees depending on the specific green innovation outcome considered, with the highest turning point observed for green product innovation. This pattern suggests that more resource-intensive forms of green innovation may require a larger organizational scale before firms can fully exploit size-related advantages.

Taken together, the results support Hypotheses 1–3 and suggest that external knowledge integration, digital capabilities, and public support are among the most important correlates of green innovation among Italian SMEs.

Prior to conducting the PCA, we assessed the suitability of the data for dimension reduction. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.628, and Bartlett's test of sphericity was highly significant ($\chi^2(6) = 1897.52$, $p < 0.001$), confirming that the data were suitable for PCA (Appendix Table C3). As a robustness check, we constructed an alternative co-creation index using PCA. The first component explains 41.8% of the total variance and all four indicators load positively on this component. Re-estimating Equation (1) using the PCA-based index yields results consistent with the equal-weighted specification (Appendix Table C4). These findings confirm that the results supporting Hypotheses 1–3 are robust to alternative constructions of the co-creation index. The main findings are also robust to alternative specifications of R&D intensity (Appendix Table E1).

To further assess the substantive similarity between the two measures, Figure 5 plots the predicted probability of green innovation across different levels of co-creation using both the equal-weighted index and the PCA-based index. The two curves are nearly indistinguishable, providing additional evidence that the main findings are not sensitive to the method used to construct the co-creation measure. Moving from the lowest to the highest level of co-creation is associated with an increase in the predicted probability of green innovation from approximately 18% to over 60%.

We further examined the four underlying co-creation channels separately, namely formal co-creation, knowledge co-creation, collaborative development, and market research. The results, reported in Appendix Table E2, indicate that all four channels are positively and significantly associated with green innovation outcomes. Knowledge co-creation exhibits the largest marginal effects, while formal co-creation and market research also show substantial positive associations. These findings suggest that the positive relationship between co-creation and green innovation is not driven by any single collaboration mechanism but reflects the broader role of external knowledge integration. The separate estimation of the four channels also addresses potential conceptual differences among the components of the co-creation index. Although market research represents a less interactive and less relational form of external knowledge acquisition than customer, supplier, or partnership-based collaboration, it remains positively associated with green innovation outcomes. This finding suggests that both relational and search-based mechanisms contribute to SMEs' sustainability-oriented innovation activities.

5.2 | Green Innovation and Firm Performance—Second Stage Estimates

Tables 7 and 8 present the second-stage results, where firm performance—measured as log value added per employee and log revenue per employee—is regressed on predicted green innovation outcomes.[8] As an additional robustness check, we re-estimated the second-stage regressions using predicted values of green innovation derived from the PCA-based co-creation index. The results are consistent with those obtained using the equal-weighted index, confirming that green innovation is positively associated with firm performance (Appendix Table C5).

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TABLE 7 | Second-stage estimates: Green innovation and value added per employee.

	(1)	(2)	(3)	(4)
Variables	**Log value added per employee**			
Predicted green innovation	0.130***	0.129***	0.0698***	0.0712***
	(0.018)	(0.020)	(0.020)	(0.020)
Log capital	—	—	0.119***	0.102***
			(0.007)	(0.007)
Firm size	—	—	—	0.102***
				(0.016)
Constant	3.782***	3.024***	2.564***	2.343***
	(0.0139)	(0.190)	(0.182)	(0.183)
Industry FE	No	Yes	Yes	Yes
Regional FE	No	Yes	Yes	Yes
Observations	5719	5719	5655	5655
R-squared	0.009	0.171	0.217	0.224

Note: Ordinary least squares (OLS) estimates are reported. The dependent variable is the natural logarithm of value added per employee. Predicted green innovation is obtained from the first-stage probit model. Industry and regional fixed effects are included in Columns (2)–(4). Robust standard errors are reported in parentheses. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

TABLE 8 | Second-stage estimates: Green innovation and revenue per employee.

	(1)	(2)	(3)	(4)
Variables	**Log revenue per employee**			
Predicted green innovation	0.221***	0.098***	0.039*	0.041*
	(0.021)	(0.022)	(0.022)	(0.022)
Log capital	—	—	0.122***	0.110***
			(0.008)	(0.008)
Firm size	—	—	—	0.072***
				(0.017)
Constant	4.895***	4.281***	3.809***	3.653***
	(0.0164)	(0.198)	(0.186)	(0.188)
Industry FE	No	Yes	Yes	Yes
Regional FE	No	Yes	Yes	Yes
Observations	5911	5911	5842	5842
R-squared	0.018	0.276	0.312	0.314

Note: Ordinary least squares (OLS) estimates are reported. The dependent variable is the natural logarithm of revenue per employee. Predicted green innovation is obtained from the first-stage probit model. Industry and regional fixed effects are included in Columns (2)–(4). Robust standard errors are reported in parentheses. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

Specifically, Table 7 reports results with log value added per employee as the dependent variable (with and without firm controls, and with and without fixed effects), while Table 8 reports the corresponding specifications using log revenue per employee.

We further account for dynamics by using the firm's decision to engage in green innovation in the base year and measuring subsequent performance (revenue and value added) in the same year and over the following 3 years (t+1, t+2, t+3). This lag structure improves the temporal ordering between innovation and performance outcomes, which helps reduce concerns related to reverse causality. This approach is widely used in applied microeconometrics and international business research (Bernard and Jensen 1999; Wagner 2007). The corresponding results are presented in Appendix Tables A1 and A2.

Additionally, we analyze the growth rates of value added and revenue over a four-year period (Appendix Table A3).[9] Columns (1) and (2) present results for predicted green innovation and four-year revenue growth (with and without firm-level controls), while Columns (3) and (4) report results for predicted green innovation and four-year growth in value added (firm productivity). The estimates remain positive and statistically significant across specifications. These results support Hypothesis 6. As an additional robustness check, we examine whether the relationship between green innovation and firm performance differs when performance is measured as the average value added and revenue per employee during the pandemic period (2020–2021) and the recovery period (2022–2023). The results, reported in Appendix Table E5, indicate that predicted green innovation remains positively and significantly associated with both value added and revenue per employee across both periods. While the estimated coefficients are somewhat larger during the recovery period, the overall pattern of results remains unchanged. These findings suggest that the positive association between green innovation and firm performance is not driven solely by pandemic-specific conditions.

While the results are consistently positive across both performance measures, the evidence is stronger for value added per employee than for revenue per employee. In the fully specified models, the coefficient on predicted green innovation remains statistically significant at the 1% level for value added, whereas the statistical significance is weaker for revenue ($p < 0.10$). This difference may reflect the fact that productivity improvements arising from green innovation can materialize more directly through efficiency gains and resource optimization, while revenue outcomes are likely to be influenced by a broader set of market conditions, customer demand factors, and competitive dynamics that are not fully captured in the model.

5.3 | Interaction Between Co-Creation and R&D Intensity

Across all models, co-creation from external demand- and supply-side actors shows a strong positive association with green innovation, while internal R&D intensity does not exhibit a significant direct association with green innovation. To explore this relationship further, Table 9 shows the associations of co-creation and R&D intensity with different forms of green

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TABLE 9 | Average marginal effects from probit models: Interaction between co-creation and R&D intensity.

Variables	(1) Green innovation	(2) Green product innovation	(3) Green process innovation	(4) Improved green characteristics	(5) Green circular economy project
Co-creation index	0.100***	0.031***	0.036***	0.061***	0.041***
	(0.004)	(0.003)	(0.003)	(0.004)	(0.003)
R&D intensity	−0.000	0.000	−0.000	0.001	−0.001
	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)
(Co-creation × R&D intensity)	0.001	0.000	−0.000	−0.000	0.000
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Export turnover	0.001***	0.000***	0.000	0.000**	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
IoT and big data	0.095***	0.055***	0.064***	0.032*	0.035***
	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)
Government support	0.090***	0.022***	0.048***	0.062***	0.037***
	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)
Firm size	−0.022*	−0.019**	−0.018**	−0.002	−0.013
	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)
Firm size^2	0.007***	0.003*	0.004***	0.002	0.005***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Firm age	0.006	−0.001	0.007	−0.002	−0.004
	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)
Industry FE	Yes	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes	Yes
Observations	6044	5863	5862	6026	5973
Pseudo R^2	0.131	0.129	0.112	0.106	0.105

Note: Average marginal effects (AMEs) from probit models are reported. The dependent variables are binary indicators of green innovation outcomes. The interaction term captures the joint association between co-creation and internal R&D intensity. All specifications include industry and regional fixed effects. Robust standard errors are reported in parentheses. Variation in sample size reflects missing values across green innovation subtypes. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

innovation (Columns 1–5). All models include a full set of controls, as well as industry and regional fixed effects.

The co-creation index is positively and significantly associated with all forms of green innovation across the models. In other words, both formal and informal external co-creation are associated with a higher likelihood of firms engaging in green innovation. By contrast, internal R&D intensity alone is not significantly associated with this likelihood. This finding is consistent with Spithoven et al. (2013), who argue that firms' internal R&D investments are often limited, making them more reliant on external information. Moreover, the interaction between co-creation and R&D intensity shows no statistically significant association in the full sample, suggesting that the two factors operate largely independently within the SME sample. This suggests that co-creation is associated with green innovation across firms with different levels of R&D intensity.

With respect to the proposed hypotheses, the results provide limited support for the direct role of internal R&D intensity. Specifically, the estimates reported in Table 6 do not indicate a statistically significant positive association between R&D intensity and green innovation in the full sample, providing no support for Hypothesis 4. Similarly, the interaction term between co-creation and R&D intensity is not statistically significant in the baseline models (Table 9), indicating that Hypothesis 5 is not supported in the full SME sample.

However, the size-split analysis provides additional insight. When the sample is divided by firm size, the interaction between co-creation and R&D intensity becomes positive and

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TABLE 10 | Average marginal effects from probit models: Interaction between co-creation and R&D intensity by firm size.

	(1)	(2)	(3)	(4)
	Green innovation			
Variables	Firms with 1–49 employees		Firms with 50–249 employees	
Co-creation index	0.111***	0.101***	0.102***	0.087***
	(0.004)	(0.005)	(0.014)	(0.018)
R&D intensity	−0.000	−0.000	−0.021**	−0.021
	(0.001)	(0.001)	(0.009)	(0.013)
Co-creation index × R&D intensity	0.001	0.001	0.011**	0.011**
	(0.001)	(0.001)	(0.004)	(0.005)
Firm controls	No	Yes	No	Yes
Industry FE	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes
Observations	5910	5516	650	446
Pseudo R^2	0.109	0.114	0.208	0.210

Note: Average marginal effects (AMEs) from probit models are reported. The dependent variable is a binary indicator of green innovation. Columns (1)–(2) report results for firms with fewer than 50 employees (micro and small firms), while Columns (3)–(4) report results for firms with 50–249 employees (medium-sized firms). Industry and regional fixed effects are included in all specifications, and firm-level controls are included where indicated. Robust standard errors are reported in parentheses. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

statistically significant for medium-sized firms (50–249 employees), as reported in Table 10. This finding suggests that internal R&D intensity strengthens the relationship between co-creation and green innovation within this subgroup. Accordingly, while Hypothesis 4 is not supported overall, Hypothesis 5 receives partial support, as complementarity between internal R&D intensity and co-creation emerges only among medium-sized firms.

The marginal effects reported in Table 10 further illustrate the economic significance of these differences. For firms with fewer than 50 employees, a one-unit increase in the co-creation index is associated with approximately a 10–11 percentage-point increase in the probability of green innovation, while the interaction between co-creation and R&D intensity remains statistically insignificant. For medium-sized firms, the interaction term becomes positive and significant, indicating that internal R&D intensity is complementary to external knowledge sourcing. Specifically, the interaction term is associated with an additional 1.1 percentage-point increase in the probability of green innovation, suggesting that medium-sized firms are better able to combine internal and external knowledge resources.

We further assessed the predictive performance of the first-stage probit models using receiver operating characteristic (ROC) analysis. The area under the curve (AUC) values range from 0.727 to 0.760 across the five green innovation outcomes (Appendix Table E3), indicating acceptable discriminatory power. Figure E1 presents the ROC curve for the baseline green innovation model. Overall, these results suggest that the first-stage models are able to distinguish firms engaging in green innovation from non-innovators with reasonable accuracy.

Table 10 shows that for micro and small firms (Columns 1 and 2), R&D intensity has neither a direct nor an indirect association with green innovation. By contrast, for medium-sized firms (Columns 3 and 4), R&D intensity does not exhibit a direct association but is indirectly associated with green innovation through co-creation, as the interaction term is statistically significant. This suggests that micro and small firms, often constrained by limited resources, rely primarily on external knowledge flows, whereas medium-sized firms, with stronger absorptive capacity and organizational structures, may be better positioned to leverage internal R&D intensity together with co-creation.

6 | Discussion

This study examines when and how co-creation with demand- and supply-side actors is associated with green innovation in SMEs, and whether such innovation relates to firm performance. While prior research has explored the relationship between stakeholder collaboration and innovation outcomes, the mechanisms through which external knowledge integration supports environmentally sustainable innovation in SMEs remain less clearly understood. Our findings provide new insights into how external knowledge sourcing, digital capabilities, and institutional support relate to green innovation outcomes.

The empirical results largely support the theoretical expectations developed in Section 2. Co-creation is positively associated with SMEs' engagement in green innovation (Hypothesis 1), while digital capabilities and government support also exhibit positive relationships with green innovation outcomes (Hypothesis 2 and 3). By contrast, internal R&D intensity does not show a direct association with green innovation across the full SME sample, although the size-split analysis indicates that R&D intensity complements co-creation among medium-sized firms (providing no support for Hypothesis 4 and partial support for Hypothesis 5). Finally, green innovation is positively associated with firm performance (Hypothesis 6), suggesting that environmentally oriented innovation may be associated with economic benefits for SMEs.

First, the results show that co-creation is positively associated with SMEs' engagement in green innovation. This finding is consistent with the open innovation literature, which emphasizes the importance of accessing distributed knowledge sources beyond firm boundaries (Chesbrough 2003; Laursen and Salter 2006). At the same time, the analysis extends this literature by showing that a multi-channel configuration of external knowledge sources—including customers, suppliers, partners, and market research—plays an important role in

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sustainability-oriented innovation. Environmental innovation often requires integrating heterogeneous knowledge related to regulation, environmental technologies, and changing market expectations that are dispersed across value chains and institutional actors. In this respect, the findings complement recent research suggesting that environmentally sustainable innovation increasingly emerges through collaborative ecosystems rather than through internal R&D activities alone (Janik and Ryszko 2025).

Second, the results suggest that co-creation is associated not only with product-oriented innovation but also with implementation-oriented forms of green change. The findings may also be interpreted in light of the growing importance of collaborative relationships following the disruptions associated with the COVID-19 pandemic. Recent studies emphasize that firms increasingly rely on inter-organizational collaboration, knowledge sharing, and coordinated responses across supply chains to address uncertainty and sustainability challenges (Sharma et al. 2022; Javed et al. 2024). From this perspective, co-creation can be viewed not only as a mechanism for innovation but also as a means of enhancing organizational adaptability and resilience. The positive association between co-creation and green innovation identified in this study suggests that collaborative knowledge networks may have become even more valuable in an environment characterized by greater uncertainty, supply-chain disruptions, and increasing sustainability pressures. Collaborative knowledge exchange appears to support both technological and organizational adjustments required for sustainability transitions. This interpretation is consistent with Barbieri et al. (2025), who emphasize the importance of linking sustainability-related findings to measurable operational and managerial outcomes. These results also highlight the importance of inter-organizational learning processes, particularly in sectors where sustainability challenges require coordinated changes throughout supply chains and production systems.

Third, the analysis provides insight into the role of digitalization within green innovation systems. While digital technologies are often discussed as drivers of industrial transformation, their role in environmentally sustainable innovation remains less well understood. The results indicate that the adoption of IoT and big data technologies is positively associated with green innovation among SMEs. The results are consistent with the view that digital technologies strengthen firms' knowledge-integration capabilities by allowing firms to monitor environmental performance, collect operational data, and coordinate information flows across supply chains. In this sense, digitalization may function as a supporting infrastructure that helps firms translate externally sourced knowledge into implementable green innovations. This interpretation aligns with recent studies suggesting that digital transformation can strengthen firms' ability to develop sustainability-oriented innovations through improved data-driven decision-making (Lee et al. 2024). It is also consistent with recent firm-level evidence suggesting that the innovation and performance benefits of digital technologies depend not only on firms' AI capabilities but also on how these capabilities are aligned with broader strategic objectives and complementary organizational capabilities (Shah et al. 2026; Shah and Cucculelli 2026). Taken together, these findings suggest that digital technologies are not merely operational tools but strategic enablers that help SMEs combine external knowledge, sustainability objectives, and organizational resilience in increasingly uncertain environments.

Fourth, the findings refine the role of internal R&D intensity in SMEs' green innovation models. The findings suggest that the relationship between internal and external knowledge sources may follow a staged or threshold-based logic. For micro and small firms, co-creation appears to partially substitute for internal R&D intensity, as external knowledge sourcing remains strongly associated with green innovation while R&D intensity and its interaction with co-creation remain insignificant. By contrast, among medium-sized firms, internal R&D intensity begins to complement external knowledge sourcing, as reflected in the positive interaction between co-creation and R&D intensity. This finding extends existing research on absorptive capacity and open innovation by showing that the balance between internal and external knowledge sources is not constant across SMEs. Prior studies have emphasized the importance of absorptive capacity for converting external knowledge into innovation outcomes (Huber et al. 2020; Francis and Chakravarty 2025) and have shown that collaborative innovation tends to be associated with stronger returns when firms possess greater internal capabilities (Park and Seo 2025). However, existing evidence provides limited insight into how this relationship varies across SME size categories in the context of green innovation. Our results suggest that sustainability-oriented innovation may evolve from a substitution logic, where firms compensate for limited internal resources through external collaboration, toward a complementarity logic in which internal R&D intensity and co-creation reinforce one another as organizational capabilities develop. This contributes to the ongoing debate on substitution versus complementarity between internal and external knowledge sources within open innovation systems (Spithoven et al. 2013).

Finally, the second-stage analysis indicates that green innovation is positively associated with firm performance, measured by value added per employee and revenue per employee. However, the association is more robust for productivity than for revenue, suggesting that the benefits of green innovation may initially emerge through operational efficiency and value creation rather than through immediate revenue expansion. These relationships remain positive when performance is measured in subsequent years, suggesting that the economic benefits of green innovation may extend beyond short-term outcomes. While the observational nature of the data does not allow definitive causal claims, the findings are consistent with the "business case" perspective of environmental innovation, which suggests that environmentally oriented innovations can enhance firm competitiveness by improving efficiency, product differentiation, and market positioning (Porter and van der Linde 1995). At the same time, the results contribute to a growing debate regarding whether sustainability-related activities translate into measurable economic benefits. Recent evidence reports mixed findings, with some studies showing that sustainability initiatives do not automatically improve organizational performance (De Matteis

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et al. 2026). Our findings suggest that the economic benefits of sustainability-oriented innovation may be more visible in productivity-related outcomes than in immediate revenue growth, highlighting the importance of considering multiple dimensions of firm performance.

More broadly, these findings contribute to ongoing debates in open and sustainable innovation research regarding how internal and external knowledge sources interact in SME innovation systems. While much of the innovation literature emphasizes the role of internal R&D capabilities, the results suggest that sustainability-oriented innovation in SMEs may follow a more network-intensive logic in which external knowledge integration plays a central role. By distinguishing between demand-side and supply-side co-creation channels and by highlighting the enabling role of digital capabilities, this study provides a more nuanced understanding of how SMEs mobilize distributed knowledge to address sustainability challenges.

Taken together, the results suggest that green innovation in SMEs is best understood as an externally oriented and capability-enabled process. Co-creation provides access to diverse knowledge inputs, digital technologies support the integration of this knowledge, and government support may help reduce financial and informational constraints that often limit SMEs' experimentation with sustainability-oriented innovations. In this respect, the study contributes to the literature by highlighting how collaborative knowledge networks, digital capabilities, and institutional support jointly shape sustainability-oriented innovation among SMEs.

7 | Conclusion and Policy Implications

This study examines the determinants and performance implications of green innovation among Italian SMEs, focusing on the role of co-creation with external actors, digital technologies, and government support. Using survey data from 6646 firms combined with financial information and a CDM-inspired two-stage econometric framework, the analysis provides large-scale evidence on how SMEs mobilize external knowledge and enabling capabilities to develop environmentally oriented innovations.

The findings contribute to the literature on sustainable and open innovation in several ways. First, the results highlight the importance of co-creation as a multi-channel external knowledge configuration. Engagement with customers, suppliers, formal partners, and market research activities is positively associated with SMEs' likelihood of developing green innovation. This finding reinforces the view that sustainability-oriented innovation in SMEs often depends on collaborative knowledge exchange rather than solely on internally generated technological capabilities.

Second, the study emphasizes the role of digital technologies as enabling capabilities that support green innovation. The positive association between the adoption of IoT and big data technologies and green innovation suggests that digitalization may strengthen firms' ability to collect, process, and integrate information relevant to environmental improvements. Digital capabilities therefore appear to facilitate the translation of externally sourced knowledge into implementable sustainability innovations.

Third, the analysis refines the understanding of internal R&D intensity in SME innovation systems. While R&D intensity does not exhibit a significant direct association with green innovation in the full SME sample, the results reveal important heterogeneity across firm sizes. Specifically, the findings suggest that green innovation may follow a staged or threshold-based logic. For micro and small firms, external co-creation appears to partially substitute for internal R&D intensity, whereas for medium-sized firms, internal R&D intensity, and co-creation appear to be complementary. This finding contributes to the ongoing debate in the open innovation literature regarding substitution versus complementarity between internal and external knowledge sources by suggesting that the relationship may vary with firms' organizational capabilities and absorptive capacity.

Overall, the results suggest that green innovation in SMEs is best understood as a network-intensive and capability-enabled process. Rather than relying primarily on internal R&D investment, SMEs appear to develop environmentally sustainable innovations through the combination of collaborative knowledge networks, digital capabilities, and supportive institutional environments. More broadly, the findings suggest that SMEs are best viewed as network-embedded innovators that create and mobilize innovation capabilities through relationships with customers, suppliers, partners, and other external actors. This perspective extends traditional innovation models that emphasize internal R&D by highlighting the importance of external knowledge integration as a central mechanism underlying sustainability-oriented innovation in SMEs.

7.1 | Policy Implications

The findings have several implications for policies aimed at accelerating the transition toward a net-zero economy. Importantly, the results suggest that policy interventions should be differentiated according to firm size. For micro firms, policies could primarily focus on reducing barriers to external collaboration by supporting participation in innovation networks, cluster initiatives, and knowledge-sharing platforms. Small firms may benefit from a combination of collaboration support and targeted digitalization programs that strengthen their ability to absorb and utilize external knowledge. For medium-sized firms, where internal R&D intensity and co-creation appear complementary, policy instruments that jointly support collaborative projects and internal innovation capabilities may be particularly relevant. These findings suggest that a one-size-fits-all approach to SME innovation policy may overlook important differences in firms' capability profiles and innovation strategies.

First, policy frameworks should complement traditional R&D-focused instruments with measures that strengthen firms' ability to collaborate and access external knowledge. Because green innovation in SMEs often depends on network-based knowledge exchange, effective policy mixes should support collaboration platforms, supply-chain partnerships, and knowledge-sharing

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initiatives that reduce coordination barriers among firms and other ecosystem actors.

Second, policies should explicitly encourage co-creation as part of SME innovation strategies. Practical instruments may include collaboration vouchers, matchmaking platforms, joint pilot projects, and advisory programs that facilitate experimentation among firms, suppliers, and customers on greener materials, process improvements, and circular economy solutions.

Third, the results highlight the importance of policies supporting green digitalization. Digital technologies such as IoT and big data may help firms monitor resource use, strengthen supply-chain transparency, and optimize production processes in environmentally beneficial ways. Policies that encourage digital adoption among SMEs—through training programs, digital infrastructure, and targeted incentives—may therefore support firms' capacity for green innovation.

Fourth, policy evaluation frameworks should move beyond traditional input indicators such as R&D expenditure and instead consider broader measures of innovation capability. Indicators related to collaboration intensity, digital adoption, and participation in innovation networks may provide a more accurate reflection of how SMEs develop sustainability-oriented innovations. Finally, regional differences in green innovation activity suggest that place-based policy approaches remain important. Tailored regional strategies that reflect local industrial structures and innovation ecosystems may help strengthen SME participation in sustainability transitions.

Taken together, these findings suggest that policies aimed at accelerating green innovation in SMEs should move beyond a narrow focus on internal technological investment and instead support the broader ecosystem conditions that enable firms to collaborate, integrate knowledge, and deploy digital capabilities for sustainability-oriented innovation.

8 | Limitations and Future Research

This study has several limitations that suggest directions for future research. First, co-creation practices and green innovation outcomes are measured using survey-based indicators. Although the integration of survey responses with administrative financial data helps reduce concerns about common method bias in performance outcomes, the measures do not fully capture the intensity, governance structures, frequency of interaction, or partner quality involved in collaboration. Future studies could combine survey measures with network data, transaction-level information, or external environmental indicators—such as environmental certifications or audited resource-use indicators—to better capture the depth and effectiveness of co-creation activities.

Second, although the two-stage empirical design and the use of subsequent-year performance outcomes improve the temporal ordering between innovation and firm performance, the analysis remains based on observational data and cannot fully rule out unobserved heterogeneity across firms, including differences in managerial capabilities, strategic orientation, organizational culture, or environmental awareness that may influence both co-creation behavior and innovation outcomes. Future research could adopt quasi-experimental approaches—such as exploiting policy eligibility thresholds, staggered policy implementation, or regional rollouts of support programs—to identify causal relationships between collaboration, digital adoption, and green innovation more precisely. In addition, although we employ robust standard errors throughout the analysis, future studies could further examine statistical inference in multi-stage innovation models using bootstrap procedures or Murphy–Topel corrections designed specifically for generated regressors. A further limitation relates to the timing of the study. The survey was conducted immediately before the COVID-19 pandemic, while the performance outcomes extend into the pandemic and post-pandemic periods. Although this feature allows us to observe longer-term performance outcomes, it also means that firms operated under substantially different economic conditions during the performance measurement period. Pandemic-related disruptions, changes in supply-chain structures, and accelerated digital adoption may have been associated with the relationships examined in this study. While the additional sensitivity analysis suggests that the main findings remain qualitatively similar across pandemic and recovery periods, future research could examine more explicitly how crisis conditions shape the relationship between co-creation, digital capabilities, green innovation, and firm performance.

Third, the empirical setting focuses on SMEs in Italy. While this context is valuable given the economic importance of SMEs and the country's substantial regional heterogeneity, it may limit the generalizability of the findings. Comparative studies across European countries or other institutional contexts could help clarify how differences in policy frameworks, industrial structures, and innovation systems shape the relative importance of co-creation, digitalization, and internal R&D in sustainability-oriented innovation. In addition, several green innovation measures are based on binary indicators capturing whether firms engaged in specific innovation activities. While these measures are widely used in innovation research, they do not capture differences in the scale, intensity, or environmental impact of innovation outcomes. Future studies could employ more granular measures of green innovation, including innovation expenditures, environmental performance indicators, patent-based measures, or sustainability-related output metrics. A further limitation concerns the measurement of digitalization. In this study, digital capabilities are proxied by the adoption of IoT and big data technologies, which capture important dimensions of firms' ability to collect, process, and utilize information. However, digital transformation is a broader phenomenon that may also include technologies and organizational practices such as cloud computing, artificial intelligence, cybersecurity, platform-based business models, and digital process integration. Consequently, the measure employed in this study should be interpreted as capturing specific digital enabling technologies that support information processing and knowledge integration rather than the full spectrum of digital transformation. Finally, although the study explores heterogeneity through separate estimations for micro, small, and medium-sized firms, it does not formally test cross-group

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differences using pooled interaction models or Chow-type tests. Accordingly, the observed differences across firm-size categories should be interpreted with appropriate caution.

Future research could extend the present study in several directions. First, researchers could examine whether the role of co-creation differs across pre-crisis, crisis, and post-crisis periods and whether collaborative knowledge networks become more valuable under conditions of heightened uncertainty. Second, future studies could investigate whether government support moderates the relationship between co-creation and green innovation, particularly during periods of economic disruption. Third, additional work could explore how different dimensions of digitalization, including artificial intelligence, cloud computing, and platform-based technologies, interact with co-creation in shaping green innovation outcomes, as well as whether digital capabilities act as a mediating mechanism through which external knowledge sourcing contributes to green innovation and sustainability performance. Fourth, future research could employ pooled interaction models or other formal cross-group comparison techniques to better understand how the relationship between co-creation, internal R&D, and green innovation varies across micro, small, and medium-sized firms. Finally, cross-country comparisons could provide insight into how institutional environments shape the relationships among co-creation, digitalization, internal R&D, and green innovation outcomes.

Author Contributions

Angela Stefania Bergantino: conceptualization, writing – original draft, methodology, supervision, project administration. **Marco Cucculelli:** conceptualization, writing – original draft, methodology, supervision. **Mario Intini:** conceptualization, writing – original draft, methodology, formal analysis. **Syed Muhammad Ali Shah:** conceptualization, investigation, writing – original draft, methodology, formal analysis, data curation.

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Endnotes

[1] We selected these four actors based on theoretical foundations, considering both demand-side and supply-side actors as sources of external knowledge. Within these two pillars, we further distinguish between formal and informal sources of knowledge on each side. Because of data constraints, however, only one representative actor could be included within each category. Thus, the selection of these pillars and actors reflects theoretical considerations first, followed by data availability.

[2] The index is computed using two alternative approaches. First, we assign equal weights to each actor. Second, we derive the index using principal component analysis (PCA). Both approaches produce similar results, supporting the robustness of the equal-weighted index used in the main analysis.

[3] A detailed overview of the data is provided in Cucculelli et al. (2024), Shah et al. (2026), and Appendix B.

[4] Regarding potential confounding events during the survey period, it is important to note that the survey was conducted prior to the onset of the COVID-19 pandemic, between October 2019 and February 2020.

[5] This study focuses on firms with up to 249 employees, covering micro, small, and medium-sized enterprises. According to the European Commission Recommendation 2003/361/EC (https://eur-lex.europa.eu/eli/reco/2003/361/oj), micro firms are defined as those with fewer than 10 employees, small firms have between 10 and 49 employees, and medium-sized firms have between 50 and 249 employees.

[6] Our model is not identical to the four-stage Crépon et al. (1998) CDM framework. In the original CDM specification, the first stage is a selection equation estimated using a Heckman model, followed by stages modeling innovation input, innovation output, and finally the impact of innovation on firm performance. By contrast, our approach is simpler and more direct: we focus on how external knowledge from demand- and supply-side actors is associated with green innovation, and how green innovation in turn is associated with firm performance. While our analysis is inspired by the CDM framework, it does not replicate its full four-stage structure.

[7] We use co-creation as an index and include its normalized value in the analysis of green innovation. All results show a statistically significant and positive association with green innovation.

[8] To address the potential scale effect between firm value added and firm size, we use value added per employee as the dependent variable. This allows us to control for firm size and better capture the productivity associations of green innovation. Results across all models (1) to (4) are positive and statistically significant. These findings indicate that green innovation is associated not only with larger firm size but also with higher labor productivity.

[9] We analyze the growth rates of firm value added per employee and revenue per employee over a four-year period. To account for the COVID-19 period, we measure firm performance using four-year growth rates of these variables.

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Appendix A

TABLE A1 | Predicted green innovation and value added over time.

	(1)	(2)	(3)	(4)
Variables	**Log value added (t)**	**Log value added (t + 1)**	**Log value added (t + 2)**	**Log value added (t + 3)**
Predicted green innovation (t)	0.067***	0.072***	0.089***	0.101***
	(0.019)	(0.020)	(0.021)	(0.022)
Log capital (t)	0.114***	0.117***	0.120***	0.123***
	(0.008)	(0.008)	(0.009)	(0.009)
Firm size (t)	1.001***	0.970***	0.956***	0.956***
	(0.012)	(0.013)	(0.013)	(0.014)
Constant	2.589***	2.997***	2.927***	2.838***
	(0.183)	(0.169)	(0.204)	(0.226)
Industry FE	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes
Observations	5719	5731	5593	5095
R-squared	0.795	0.784	0.766	0.744

Note: Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

TABLE A2 | Predicted green innovation and firm's revenue over time.

	(1)	(2)	(3)	(4)
Variables	**Log revenue (t)**	**Log revenue (t + 1)**	**Log revenue (t + 2)**	**Log revenue (t + 3)**
Predicted green innovation (t)	0.072***	0.086***	0.111***	0.125***
	(0.021)	(0.022)	(0.025)	(0.026)
Log capital (t)	0.164***	0.167***	0.169***	0.176***
	(0.009)	(0.010)	(0.011)	(0.011)
Firm size (t)	0.862***	0.847***	0.840***	0.828***
Constant	(0.013)	(0.014)	(0.015)	(0.016)
	4.107***	4.249***	4.277***	4.385***
	(0.194)	(0.198)	(0.213)	(0.207)
Industry FE	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes
Observations	5906	5808	5693	5169
R-squared	0.744	0.728	0.691	0.678

Note: Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

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TABLE A3 | Green innovation and firm growth: Revenue and value added.

	(1)	(2)	(3)	(4)
Variables	**Growth in revenue**		**Growth in value added**	
Predicted green innovation	0.071***	0.060***	0.051**	0.047**
	(0.019)	(0.020)	(0.020)	(0.021)
Log capital	—	−0.006	—	−0.004
		(0.007)		(0.007)
Firm size	—	0.024**	—	0.014
		(0.011)		(0.012)
Constant	0.290***	0.252**	0.0512	0.0288
	(0.102)	(0.105)	(0.149)	(0.152)
Industry FE	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes
Observations	5145	5097	5042	4994
R-squared	0.039	0.042	0.039	0.040

Note: Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

Appendix B: Survey Design and Sample Characteristics

B.1 | Sampling Criteria

The sampling frame was constructed using the Moody's Bureau van Dijk AIDA database. Firms were included in the sampling frame if they satisfied the following criteria:

1. Located in Italy
2. Active in 2019
3. Firms were included in the original survey sampling frame if they had fewer than 3000 employees. For the purposes of the present study, the analytical sample was restricted to firms meeting the European Commission definition of SMEs (fewer than 250 employees).
4. Not a subsidiary, foreign firm, non-profit organization, or public institution
5. Availability of telephone numbers or email addresses for contact

Applying these criteria resulted in a sampling frame of 64,872 firms. From this broader survey population, the present study retains only firms satisfying the European Commission definition of SMEs (fewer than 250 employees). As confirmed by the final matched dataset, no firm in the analytical sample exceeds this threshold. The survey targeted senior decision-makers responsible for strategic or innovation-related activities within the firm, such as chief executive officers, chairpersons, or senior managers.

B.2 | Geographical Distribution of Surveyed Firms Across NUTS-2 Regions

Region	Survey distribution (percentage)
Lombardia	22.30%
Veneto	12.85%
Emilia-Romagna	11.17%
Marche	7.89%
Lazio	7.35%
Piemonte	7.04%
Toscana	6.37%
Campania	3.78%
Trentino-Alto Adige	3.41%

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Region	Survey distribution (percentage)
Puglia	3.61%
Friuli-Venezia Giulia	3.13%
Abruzzo	2.31%
Sicilia	2.46%
Umbria	1.39%
Sardegna	1.33%
Liguria	1.37%
Basilicata	0.70%
Calabria	0.96%
Molise	0.35%
Valle d'Aosta	0.22%

B.3 | Industry Distribution by NACE Section Code

NACE section	Survey distribution (percentage)
A (Agriculture, Forestry and Fishing)	0.56%
B (Mining and Quarrying)	0.17%
C (Manufacturing)	36.37%
D (Electricity, Gas, Steam and Air Conditioning Supply)	0.39%
E (Water Supply; Sewerage, Waste Management)	1.30%
F (Construction)	7.57%
G (Wholesale and Retail Trade)	12.76%
H (Transportation and Storage)	3.04%
I (Accommodation and Food Service)	2.33%
J (Information and Communication)	13.76%
K (Financial and Insurance Activities)	1.17%
L (Real Estate Activities)	1.04%
M (Professional, Scientific and Technical Activities)	12.09%
N (Administrative and Support Service Activities)	3.39%
P (Education)	0.54%
Q (Human Health and Social Work Activities)	1.74%
R (Arts, Entertainment and Recreation)	0.91%
S (Other Service Activities)	0.89%

Note: Percentages refer to the share of surveyed firms in the final sample ($N = 6646$) classified under each NACE section code.

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Appendix C: Principal Component Analysis (PCA)

TABLE C1 | Principal component loadings for co-creation variables.

Variables	Comp1	Comp2	Comp3	Comp4
Formal co-creation	0.425	0.673	−0.573	0.195
Knowledge co-creation	0.577	−0.318	−0.192	−0.727
Collaborative development	0.544	−0.523	0.013	0.657
Market research	0.436	0.416	0.796	−0.046

TABLE C2 Eigenvalues and explained variance.

Component	Eigenvalue	Proportion of variance	Cumulative
Comp1	1.672	0.418	0.418
Comp2	0.888	0.222	0.640
Comp3	0.830	0.208	0.848
Comp4	0.610	0.153	1.000

TABLE C3 | PCA diagnostics.

Diagnostic	Value
KMO measure of sampling adequacy	0.628
Bartlett test χ^2 (6)	1897.52***
Bartlett test *p*-value	<0.001
Correlation with equal-weighted index	0.997
Observations	6646

Note: The KMO statistic indicates acceptable sampling adequacy for principal component analysis. Bartlett's test rejects the null hypothesis of an identity correlation matrix, supporting the suitability of the data for dimension reduction.

As a robustness check, we conducted a principal component analysis (PCA) on the four co-creation variables: *formal co-creation, knowledge co-creation, collaborative development*, and *market research*. Prior to extraction, we assessed the suitability of the data for PCA. The KMO measure of sampling adequacy was 0.628, indicating acceptable adequacy for dimension reduction. Bartlett's test of sphericity was highly significant ($\chi^2(6) = 1897.52$, $p < 0.001$), confirming that the correlation matrix was suitable for factor extraction.

The results, reported in Table C1, show that the first principal component (Comp1) has an eigenvalue of 1.67, explaining 41.8% of the total variance. All four indicators load positively on this component, with factor loadings ranging from 0.425 to 0.577, suggesting the existence of a common underlying dimension capturing firms' engagement in external knowledge sourcing and co-creation activities. The remaining components have eigenvalues below one and explain substantially less variation. Consistent with standard PCA criteria, the first component was retained and used to construct a PCA-based co-creation index.

The PCA-based index is highly correlated with the equal-weighted co-creation index ($r = 0.997$), indicating that both measures capture essentially the same underlying construct. The robustness results reported in Table C4 remain substantively consistent with the baseline specifications, confirming that the main findings are not sensitive to the construction of the co-creation measure.

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TABLE C4 | Green Innovation and PCA co-creation index (average marginal effects).

	(1)	(2)	(3)	(4)	(5)
Variables	**Green innovation**	**Green product innovation**	**Green process innovation**	**Improved green characteristics**	**Green circular economy project**
PCA co-creation index	0.092***	0.028***	0.032***	0.056***	0.038***
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
R&D intensity	0.001	0.000	−0.001	0.001	0.000
	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)
Export turnover	0.001***	0.000***	0.000	0.000**	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
IoT and big data	0.097***	0.055***	0.065***	0.033**	0.035***
	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)
Government support	0.091***	0.022***	0.049***	0.062***	0.038***
	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)
Firm size	−0.022*	−0.019**	−0.017**	−0.002	−0.014
	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)
Firm size^2	0.007***	0.003*	0.004***	0.002	0.005***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Firm age	0.005	−0.001	0.007	−0.002	−0.005
	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)
Industry FE	YES	YES	YES	YES	YES
Regional FE	YES	YES	YES	YES	YES
Observations	6044	5863	5862	6026	5973
Pseudo R^2	0.130	0.128	0.111	0.106	0.104

Note: Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

TABLE C5 | Green innovation and firm performance.

	(1)	(2)	(3)	(4)
Variables	**Log revenue per employee**		**Log value added per employee**	
Predicted green innovation	0.115***	0.0899***	0.142***	0.0718***
	(0.023)	(0.023)	(0.020)	(0.020)
Log capital	—	0.167***	—	0.119***
		(0.009)		(0.008)
Firm size	—	−0.131***	—	0.005
		(0.013)		(0.012)
Constant	4.230***	3.896***	3.059***	2.571***
	(0.196)	(0.189)	(0.193)	(0.185)
Industry FE	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes
Observations	6026	5958	5834	5770
R-squared	0.278	0.332	0.172	0.220

Note: Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

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Appendix D: Survey Items and Variable Coding

TABLE D1 | Survey items and variable coding.

Construct	Survey item	Coding
Green innovation	With reference to the Circular Economy and the Green Economy, the company has: developed a new green product, developed green production processes, improved green characteristics of existing products or processes, or launched Circular/Green Economy projects	1 if at least one activity reported; 0 otherwise
Green product innovation	A new green product has already been developed	1 = Yes; 0 = No
Green process innovation	Green production processes have already been developed	1 = Yes; 0 = No
Improved green characteristics	Improved green characteristics of existing products or processes	1 = Yes; 0 = No
Green circular economy projects	Projects aimed at the Circular/Green Economy launched	1 = Yes; 0 = No
Knowledge co-creation	Continuous exchange of information with customers	1 = Yes; 0 = No
Collaborative development	Information from suppliers	1 = Yes; 0 = No
Market research	Market research	1 = Yes; 0 = No
Formal co-creation	Formalized new partnerships with customers, suppliers or competitors	1 = Yes; 0 = No
Digital technologies (IoT & big data)	IoT, Big Data, Industry Analytics adopted by the firm	1 = Yes; 0 = No
Export turnover	Firm's international competitiveness	1 = Yes; 0 = No

Note: This table reports the questionnaire items used to construct the principal survey-based variables included in the empirical analysis. The survey was administered between October 2019 and February 2020. The survey instrument was developed drawing on established measures used in the innovation, open innovation, co-creation, and green innovation literature and adapted to the context of Italian SMEs. All survey-based variables were coded as binary indicators, where 1 denotes the presence or adoption of the activity and 0 otherwise. The green innovation variable is a composite indicator equal to one when the firm reported at least one of the four environmentally oriented innovation activities. The co-creation index is constructed from four external knowledge channels: formal co-creation, knowledge co-creation, collaborative development, and market research. The baseline specification uses an equal-weighted index, while Appendix C reports robustness tests based on a principal component analysis (PCA) index.

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Appendix E: Robustness Checks

TABLE E1 | Alternative specification using winsorized R&D intensity (average marginal effects).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Using winsorized R&D intensity					Using log R&D intensity				
Variables	Green innovation	Green product innovation	Green process innovation	Improved green characteristics	Green circular economy project	Green innovation	Green product innovation	Green process innovation	Improved green characteristics	Green circular economy project
Co-creation index	0.101***	0.031***	0.036***	0.061***	0.042***	0.101***	0.031***	0.036***	0.061***	0.042***
	(0.004)	(0.003)	(0.003)	(0.004)	(0.003)	(0.004)	(0.003)	(0.003)	(0.004)	(0.003)
R&D intensity	0.002	0.001	−0.006*	0.000	0.001	—	—	—	—	—
Log R&D intensity	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)	0.014	0.006	−0.018*	0.007	0.002
	—	—	—	—	—	(0.012)	(0.006)	(0.010)	(0.010)	(0.008)
Export turnover	0.001***	0.000***	0.000	0.000**	0.000*	0.001***	0.000***	0.000	0.000**	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
IoT and big data	0.095***	0.055***	0.064***	0.033*	0.034***	0.095***	0.054***	0.064***	0.032*	0.034***
	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)
Government support	0.090***	0.022***	0.048***	0.062***	0.037***	0.090***	0.021***	0.048***	0.062***	0.037***
	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)
Firm size	−0.023*	−0.019**	−0.017**	−0.002	−0.014	−0.023*	−0.019**	−0.017**	−0.002	−0.014
	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)
Firm size^2	0.007***	0.003*	0.005***	0.002	0.005***	0.007***	0.003*	0.005***	0.002	0.005***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Firm age	0.005	−0.001	0.007	−0.002	−0.004	0.006	−0.001	0.007	−0.002	−0.004
	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6044	5863	5862	6026	5973	6044	5863	5862	6026	5973
Pseudo R^2	0.131	0.129	0.113	0.106	0.105	0.131	0.130	0.112	0.106	0.105

Note: Average marginal effects from probit models are reported. Columns (1)–(5) use a winsorized measure of R&D intensity (1st and 99th percentiles). Columns (6)–(10) use the natural logarithm of R&D intensity. All models include industry and regional fixed effects. Robust standard errors are reported in parentheses. The results remain substantively unchanged across specifications. Robust standard errors in parentheses.

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$.

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TABLE E2 | Green innovation and individual co-creation channels (average marginal effects).

	(1)	(2)	(3)	(4)	(5)
Variables	**Green innovation**	**Green product innovation**	**Green process innovation**	**Improved green characteristics**	**Green circular economy project**
Formal co-creation	0.099***	0.038***	0.043***	0.051***	0.049***
	(0.012)	(0.007)	(0.008)	(0.010)	(0.008)
Knowledge co-creation	0.155***	0.018**	0.044***	0.098***	0.047***
	(0.012)	(0.008)	(0.009)	(0.011)	(0.009)
Collaborative development	0.046***	0.018**	0.018**	0.040***	0.021**
	(0.013)	(0.007)	(0.009)	(0.011)	(0.009)
Market research	0.096***	0.054***	0.039***	0.050***	0.053***
	(0.014)	(0.007)	(0.009)	(0.011)	(0.009)
R&D intensity	0.001	0.000	−0.001	0.001	0.000
	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)
Export turnover	0.001***	0.000***	0.000	0.000**	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
IoT and big data	0.093***	0.053***	0.063***	0.033**	0.033**
	(0.020)	(0.010)	(0.012)	(0.017)	(0.013)
Government support	0.089***	0.021***	0.048***	0.062***	0.037***
	(0.013)	(0.007)	(0.008)	(0.011)	(0.009)
Firm size	−0.024*	−0.019**	−0.018**	−0.003	−0.014*
	(0.013)	(0.008)	(0.008)	(0.010)	(0.008)
Firm size^2	0.007***	0.003*	0.005***	0.002	0.005***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Firm age	0.006	0.001	0.008*	−0.002	−0.003
	(0.007)	(0.004)	(0.004)	(0.005)	(0.004)
Industry FE	YES	YES	YES	YES	YES
Regional FE	YES	YES	YES	YES	YES
Observations	6044	5863	5862	6026	5973
Pseudo R^2	0.135	0.135	0.113	0.109	0.107

Note: Average marginal effects from probit models are reported. The composite co-creation index is replaced by its four constituent dimensions: formal co-creation, knowledge co-creation, collaborative development, and market research. All models include industry and regional fixed effects. Robust standard errors are reported in parentheses. Robust standard errors in parentheses.
***$p < 0.01$.
**$p < 0.05$.
*$p < 0.1$.

TABLE E3 | ROC-AUC statistics for first-stage probit models.

Outcome	**AUC**
Green innovation	0.737
Green product innovation	0.760
Green process innovation	0.739
Improved green characteristics	0.727
Green circular economy project	0.732

Note: AUC values above 0.70 indicate acceptable discriminatory power.

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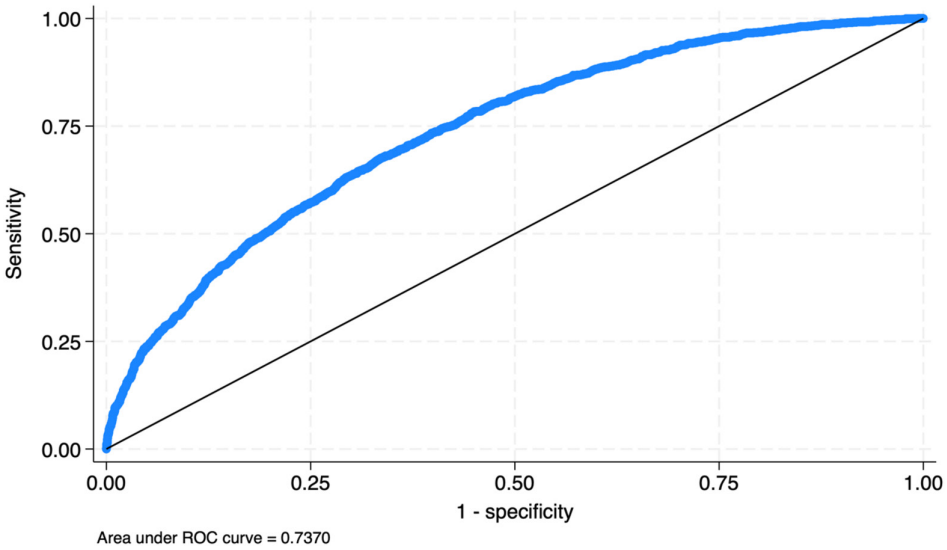


FIGURE E1 | ROC curve for the green innovation probit model. *Note:* The figure reports the receiver operating characteristic (ROC) curve for the baseline green innovation model reported in Table 6. The area under the curve (AUC) equals 0.737, indicating acceptable discriminatory power. Similar AUC values are obtained for the remaining green innovation outcomes and are reported in Table E3.

TABLE E4 | Firm size turning points in green innovation models.

Outcome	β_1 (firm Size)	β_2 (firm Size^2)	Turning point: $-\beta_1/(2\beta_2)$	Employees = exp. (turning point)	Approximate employees
Green innovation	−0.022	0.007	1.544	4.68	5
Green product innovation	−0.019	0.003	3.133	22.94	23
Green process innovation	−0.018	0.004	1.954	7.06	7
Improved green characteristics	−0.002	0.002	0.425	1.53	2
Green circular economy project	−0.014	0.005	1.321	3.75	4

Note: The turning point is calculated as $-\beta_1/(2\beta_2)$, where β_1 is the coefficient on Firm Size and β_2 is the coefficient on Firm Size^2. Since firm size is measured as the natural logarithm of employees, turning points are converted into employee counts by exponentiating the estimated value.

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TABLE E5 | COVID-period sensitivity analysis: Green innovation and firm performance.

	(1)	(2)	(3)	(4)
	Pandemic	Recovery	Pandemic	Recovery
	Average value added per employee		Average revenue per employee	
Variables	**2020–2021**	**2022–2023**	**2020–2021**	**2022–2023**
Predicted green innovation	0.069***	0.100***	0.089***	0.134***
	(0.019)	(0.022)	(0.022)	(0.025)
Log capital	0.120***	0.123***	0.170***	0.179***
	(0.007)	(0.008)	(0.009)	(0.010)
Firm size	0.984***	0.960***	0.852***	0.829***
	(0.012)	(0.013)	(0.013)	(0.015)
Constant	2.811***	2.861***	4.078***	4.215***
	(0.150)	(0.209)	(0.188)	(0.205)
Industry FE	YES	YES	YES	YES
Regional FE	YES	YES	YES	YES
Observations	5509	4987	5737	5091
R-squared	0.803	0.765	0.735	0.685

Note: The table reports second-stage OLS estimates examining the association between predicted green innovation and firm performance during the pandemic period (2020–2021) and the post-pandemic recovery period (2022–2023). Predicted green innovation is obtained from the first-stage probit model. All specifications include log capital, firm size, industry fixed effects, and regional fixed effects. Robust standard errors are reported in parentheses. Pandemic-period outcomes are measured as the average of firm performance in 2020–2021, while recovery-period outcomes are measured as the average of firm performance in 2022–2023. Robust standard errors in parentheses.

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$.

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