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RESEARCH

Strategies and drivers of innovations in the circular context: The case of Italian SMEs

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Abstract

The circular revolution has emerged as one of the greatest current and future challenges for Europe and globally. In this new paradigm shift, everyone is called to contribute, from consumers to firms. Small and medium-sized firms, thanks to their size, dynamism, and strong presence across Europe, can play an active role in driving change. Their innovative activities/approaches can guide them both toward a circular future and toward the path of sustainable growth. This work aims to analyze the drivers that push firms to adopt a circular innovation path, using data from a two-period survey of Italian manufacturing SMEs. By focusing on key variables identified in the literature, the results demonstrate a certain heterogeneity among the drivers influencing the five categories of circular innovation considered.

Keywords Eco-innovation · Circular innovation · SMEs · Circular economy

JEL Classification O31 · Q55 · Q56 · O33

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1 Introduction

The pressing need to combat climate change and environmental degradation has demanded a robust global response. With the world population now surpassing 8 billion, the impacts of environmental decline and resource depletion are intensifying at unprecedented levels. The scale of these challenges emphasizes the need for immediate, coordinated action across regions. While the focus must be on restoring a proper socio-economic-environmental balance, actions across different fronts of human activity are needed. This requires joint effort.

The European Union (EU) has demonstrated the clear and pressing need for a shift toward more sustainable socio-technical frameworks. This understanding lies at the heart of the 2019 European Green Deal, which to date represents the most comprehensive strategy for the business–economic–political dynamics needed for transitioning to a climate-neutral, resilient world. EU targets for 2030 (the Climate and Energy Framework, and the Energy Union) and especially for 2050 (i.e., 2050 climate neutral economy and the 2050 objective of the Environment Action Programme), pose challenges for substantial economic and social transformations, leading to a new vision in which sustainability underpins overall development.

Transitioning our modern economies from fossil fuels to deep decarbonization, as well as the broader effort of ensuring compatibility between human prosperity and planetary boundaries, represents one of the most profound socio-economic revolutions in human history (Mazzanti and Zecca 2023). How to reach these challenging targets remains an open debate, given the diverse interests involved. What has become clear, however, is that the transition requires a radical change in our *system of thinking*. It involves transforming production and consumption systems and redefining our concept of lifestyle. Only penetrating and broad-ranging actions across social, technological, economic, and political spheres can support the required change. As Edmonson et al. (2019) stated, the transition to a circular economy (CE) is highly influenced by composition, innovation, intensity, policy settings, and the evolution of new green markets. The increasing relevance of digitalization has been highlighted in the literature (Pagoropoulos et al. 2017), and is reinforced in the New Industrial Strategy for Europe (2020), which focuses on the need for the environmental revolution to go hand in hand with the digital revolution, as a twin transition. Within this scenario, the CE is increasingly seen by policymakers as an innovative approach to sustainable development, one that goes beyond a model based on materials loops aimed at resource and waste reduction (Geissdoerfer et al. 2017).

Considering the state of the world, innovation is among the relevant catalysts for the sustainable transition. According to the European Environmental Agency (2014), innovation is commonly regarded as the most effective response to sustaining current standards of living and overcoming environmental concerns. Innovation plays a key role in the fulfilment of the CE strategy (EEA 2016). The literature has debated for decades on the role of eco-innovation (EI) (Kemp 1997; Rennings 2000; Kemp and Foxon 2007; Arundel and Kemp 2009), its impact on

SMEs (Horbach et al. 2013; Horbach 2016), while introducing new innovative strategies and the resulting benefits, represents a central theme in the evolving transition debate (Porter 1991; Porter van der Linde 1995). Moreover, the heterogeneity of technological and environmental performance across sectors requires in-depth meso- and micro-analyses to unveil the relevant macroeconomic determinants (UNIDO 2016). The relationship between EI and the CE is also being debated in the literature. Chioatto et al. (2024) clarified that while eco-innovation refers to a new solution that reduces environmental harm, for it to be seen as circular, it must adhere to the principle of circularity. This highlights the absence of a bidirectional relationship between the two concepts: while all circular innovations are eco-innovations, the reverse is not necessarily true. Another aspect related to CI and EI is a potential drawback highlighted in the economic literature: the rebound effect. This occurs when efficiency gains from innovation lead to increased overall resource consumption, thereby offsetting some of the expected environmental or economic benefits. However, this issue has not been extensively addressed in the economics literature.

The role of SMEs is particularly relevant in this context. According to the European SMEs Annual Report, in 2024, SMEs constituted 99.8% of all European firms. They accounted for two-thirds of EU employment and generated approximately half of Europe’s gross domestic product. They are also increasingly adding value to every sector of the economy (Katsinis et al. 2024). De Jesus Pacheco et al. (2017) reviewed the determinants of eco-innovation for manufacturing SMEs, emphasizing their role in transitioning to sustainable development.

Building on this research strand, which examines the role of SMEs in green innovation, this paper analyzes the eco-innovation drivers associated with the circular paradigm for SMEs in the Italian manufacturing sector. Exploiting panel data covering the 2-year periods 2018–2019 and 2020–2021, the paper aims to combine various circular innovation strategies with different firm characteristics to identify the enabling factors. The methodology leverages the panel framework of the dataset, controlling for unobserved heterogeneity and focusing on the role of environmental knowledge among management, education for employees, skills, and R&D investments, while controlling for export trade and sector type.

The study aims to assess the influence of enabling factors across two dimensions. The first dimension considers the simple choice of whether or not to adopt at least one circular innovation per type (i.e., innovative practices/actions that are new to the firm, the market, or the entire world and that represent new alternative solutions aimed at pursuing closing the loop), while the second considers the intensity of adoption based on the number of circular innovations adopted per type. In both cases, we identified differences among the categories of circular innovations considered and aimed to capture the degree of heterogeneity in the stimulating factors across the categories involved.

Section 1 introduces the topic, Sect. 2 analyzes the literature framework, Sect. 3 explains the methodology and empirical analysis, Sect. 4 presents the results, Sect. 5 discusses the main findings and offers some policy insights, and, finally, Sect. 6 provides some brief conclusions.

2 Literature review

The link between sustainable development (SD) and innovation is a widely discussed topic in the literature. While definitions of EI (Kemp 2000, 2010; Barbieri et al. 2016) highlight the ecological attributes of specific new processes, products, and methods, a clear definition of circular economy remains elusive. Several studies (Kirchherr et al. 2017; Zotti and Bigano 2019) have surveyed the issue of defining CE; however, they were unable define a clear and shared framework.

The main objective of the CE is to replace the take-make-dispose culture with a closed-loop system where all resources are used as many times as possible, introducing new circular innovation practices to break the vicious current circle and to avoid path dependency (Joensuu et al. 2020). As Chioatto and Zecca (2023) stated, the principles and interpretations of CE may vary among theorists and across geographical locations, but they share the common goal of decreasing the use of raw materials and preventing waste by maintaining the value of products as long as possible.

Boulding (1962) was the first economist to approach the concept of a circular economy through his intuition of defining the economic system in a closed and non-linear framework, linking it with the natural limits of planet Earth. He interpreted the interrelation of the socioeconomic and environmental system normatively as the ‘spaceship economy’, which by definition should be considered as a circular system.

Boulding’s circular system was further developed by Stahel (1982), who was the first to suggest an economy made of spiral loops based on reuse, repair, reconditioning of damaged goods, and recycling aimed at extending the life-cycle of physical capital in an economy, and reducing pressure on natural resources by limiting the extraction of virgin material, avoiding waste and decreasing pollution. In Stahel’s view, closing the materials and energy loops within the economy would generate important benefits for economic progress and social well-being. It would completely revise the production–consumption–waste cycle based on rapid obsolescence, and the substitution of goods and physical capital (Stahel 1982). The rapid deterioration and irreparability of the objects on which Stahel based his view of modern capitalism are key to both value-added creation and absorption. He believed a portion of the generated global income is dedicated to substituting the value lost by depreciated goods as well as physical capital, which leads to cyclical stagnations of an economy. In a linear world, economic growth is possible only by continually reducing product lifetimes, with a continuous marginal decrease in the system’s productivity. The author considered the ‘closed-economic’ system, based on a hierarchy of closed loops (reuse, repair, recondition, recycle), to best retain the value created in the economy, thereby guaranteeing well-being, progress, and environmental conservation (Stahel 1982). Shifting to a circular economy can transform the structure of an economy toward more knowledge-intensive sectors (e.g., services and manufacturing for circularity), characterized by high-added value activities, while at the same time reducing the reliance on extraction and heavy industry, which are characterized by high energy intensity and high levels of pollution (Stahel 1982).

In this framework, firm-level innovation and industry transformations are crucial for the transition to a circular system. De Jesus and Mendonça (2018) stressed the importance of EI as a transformative process leading to greater circularity on the path toward circular innovation. With support for circular innovations (i.e., practices/actions that are new to the firm, the market, or the world and that represent new alternative solutions aimed at closing the loop), the process of transforming the economy can occur at the micro, meso, and macro levels. These innovations enable firms to redesign products, processes, and business models to minimize waste and resource use. At the meso-level, industrial symbiosis and collaborative networks can optimize material and energy flows within regions or sectors. At the macro scale, circular innovations drive systemic shifts in policy, infrastructure, and consumer behavior, fostering the transition towards a regenerative, sustainable economy. Such multilevel impacts highlight the critical role of innovation in operationalizing the principles of the circular economy across different layers of society and governance.

This argument has been present in the literature since 2009, when Carrillo-Hermosilla et al. (2009) assessed the capacity of EI to enhance new business opportunities and strategies, as well as foster change throughout the whole economic system.

Following this school of thought, the role of firms is central to ensuring the transition. The new strategies require firms to change their business models. This requirement creates the need to place innovative choices within models that are capable of allowing them to modify increasingly circular processes, products, and organizations (Kemp and Foxon 2007). Chioatto et al. (2024) noted that introducing CE-oriented innovations in business models represents strategic value-added for firms. In this manner, firms can avoid environmental degradation while gaining economic benefits (Pieroni et al. 2019). Introducing eco-innovation in a circular context translates into the practical application of circular business models (Managi and Kumar 2018).

Given the crucial role of firms, analyzing sustainable transition, within the Italian context, requires considering the role of SMEs. According to the OECD (2022), SMEs represent the vast majority of Italian firms (99.9%), with micro-firms accounting for 95%. Based on 2019 data, SMEs employ around 80% of the industrial and service labor force and generate approximately two-thirds of turnover and value added. Despite the overall level of emissions and lower emission-intensity compared to larger firms, SMEs contribute significantly to climate change and environmental impacts. Hence, their role in terms of sustainability and circularity should be better considered when designing environmental policies. This could be due to SMEs having lower marginal costs of abatement compared to large firms, which are often involved in hard-to-abate emission sectors (Sage Group 2022). According to the literature (Cuerva et al. 2014; Passaro et al. 2022), to accelerate the development of eco-innovative processes and maximize the positive externalities generated by SMEs, a deeper understanding of the factors affecting the introduction of EIs is crucial.

The main contributions of SMEs to sustainability are derived from the innovation of new technologies and processes that improve firms' environmental performance, both in terms of environmental impact (i.e., waste and pollution) and material metabolism (i.e., resource extraction). Eurobarometer's recent survey "SMEs, resource efficiency and green markets", conducted on a representative sample of

13,124 EU firms, identified that the vast majority (93%) have initiated an EI adoption processes pertaining to energy saving and waste reduction (66%), reducing the use of materials (57%) and water (49%), recycling and reuse (48%), and self-production of energy from renewable sources (12%). According to the survey, EU firms mainly rely on internal resources, both financial (60%) and capabilities (57%) for EI adoption, while only 20% of firms outsource the innovation process (e.g., consultancy for innovation, external R&D). The main barriers to adopting EI and sustainable practices are financial constraints for supporting EI (42%), the inability to identify potential new markets and customers (29%), and technical support for the development of new products, services, or processes (26%). In addition, another crucial aspect affecting EI adoption is marketing activities and delivery (27%) (Eurobarometer 2024).

SMEs are increasingly acknowledged as pivotal agents in the circular economy transition, given their capacity for flexible innovation and localized impact (FEEM 2019, 2020; Marin et al. 2015). Nonetheless, their effective engagement in the ecological transition is often hampered by structural barriers, most often financial limitations and inadequate institutions.

Empirical evidence highlights that the severity of financial constraints faced by SMEs is inversely related to the strength of institutional frameworks, as demonstrated by Ullah (2020). Furthermore, regulatory heterogeneity across countries, with non-harmonized environmental legislation, can significantly influence the effectiveness of eco-innovation and transition strategies (Costantini and Mazzanti 2012; Ambec et al. 2013).

Accordingly, policy interventions should prioritize reducing financial barriers and introducing institutional support mechanisms to facilitate SMEs' green transitions. This entails fostering synergies between designing environmental policies and competitiveness-enhancing frameworks to unlock the full potential of SMEs as drivers of sustainable transformation.

The vast body of literature that attempts to analyze factors capable of influencing firms' eco-innovation choices specifically for SMEs mainly confirms the Eurobarometer's 2024 Survey findings, that firms are enablers of adoption. In particular, two categories have been identified in the literature (Horbach 2008, 2016; Horbach et al. 2013; Parrilli et al. 2023) that can stimulate firms' innovation activities. They are: those related to technology (technology push) and those related to the market (market pull). The first category considers innovations driven by technological and research advancements. In this context, internal R&D activities and the adoption of environmental management systems within firms contribute significantly to eco-innovation. The second category focuses on demand-related factors that encourage firms to innovate, such as expectations regarding future demand.

In light of these considerations, the active participation of SMEs in sustainable transition is generally influenced by their intrinsic characteristics. The literature describes them as being reactive, flexible, and innovative organizations (Terzioski 2010; Lichtenthaler 2016). This has been confirmed by the fast post-pandemic recovery of many SMEs (and especially micro-firms), which outperformed large firms in terms of real value added and employment growth rate, highlighting their crucial importance in driving economic expansion and employment (Katsinis et al.

2024). Following this strand of literature, SMEs operate in very competitive markets. According to Love and Roper (2015) and Tang et al. (2018), the introduction of innovations and/or new business models enables them to stand out from the competition by improving their results and business performance. This means that investing in EI could lead to a competitive advantage, as previously mentioned, which, however, requires particularly large financial investments for the SMEs. The lack of financial resources and time is often mentioned as factors that prevent SMEs from developing environmentally sustainable strategies (Burlea-Schiopoiu and Stelian Mihai 2019). SMEs are typically more vulnerable to additional financial expenditures arising from green initiatives than large firms (Oakdene Hollins 2011; Rademaekers et al. 2011). Moreover, as the literature stresses (Revell and Blackburn 2005; Yacob and Moorthy 2012), there are other costs and obstacles for SMEs, such as the lack of time and human resources required by firms for making environmental improvements and implementing 'green' innovations. Pronti et al (2023) argued that achieving these structural changes requires strong synergies and considerable investments in training, research, and new technologies. Furthermore, the organizational structure may also represent a factor influencing firms' green solutions.

Innovation is beneficial not only for the environment and society as a whole, but it is also extremely linked to profitability and firms' competitiveness. As highlighted in the Draghi report, one of the main benefits of greening EU firms is the reduction of energy costs, which are significantly higher in the old continent than the price of electricity and gas in the US and China (Draghi 2024). Apparently, the behavior of EU SMEs is in line with cost-efficiency. In fact, the main types of EI adoption declared by firms in the Eurobarometer survey are all related to cost-minimization strategies, which also have positive externalities (i.e., the reduction of material extraction, pollution) and are indirectly linked to the real objective of firms (Eurobarometer 2024).

Moreover, the beneficial effects in terms of potential increases in profit margin gained with cost reduction and material optimization could also convince firms of the positive relationship between green solutions and growth. As Del Rio et al. (2016) highlighted, EI could increase the prestige of companies in international markets, earning the trust of that segment of environmentally conscious consumers. From this perspective, CE represents a chance for SMEs to achieve sustainability in the long run since it guarantees the availability and accessibility of resources in the future (Moore and Manring 2009; EMF 2015). Thus, the knowledge firms need to make strategic choices is crucial also for supporting them with the proper decisions and policy instruments.

Among the various factors influencing the decision as well as the intensity of EI adoption are, as already mentioned, the specific characteristics of firms, which become more influential within the SME framework.

One is the proactive attitude of management on environmental issues. In the context of SMEs, the manager is often also the owner of the firm, which implies a high degree of control over the strategic decision-making process. Consequently, the manager's environmental attitudes and personal values on sustainability and the natural environment can play a pivotal role in shaping the firm's propensity to adopt both eco-innovations and circular economy practices (Pronti et al. 2023). This aspect is confirmed by Lappalainen and Niskanen (2012), who argued that the ownership structure affects both the growth and the profitability of small private firms, and by Andersén (2021) and Khan and Muktar (2020), who highlighted that management's proactive role in fostering environmental awareness can be a driver of EI adoption.

Amid rapid digital and ecological transitions, the strategic use of know-how is increasingly vital for gaining and maintaining competitive advantage (Pronti et al. 2023; Antonioli et al. 2013). Recent literature (Andersén 2021; Khan and Muktar 2020) emphasizes the importance of proactive environmental management and the organizational capabilities that support it. In line with this, human resource practices, particularly recruitment and employee training, play a central role in enhancing a firm's knowledge base and its absorptive capacity, which can be defined as the ability to recognize the value of new external information, assimilate it, and apply it for commercial purposes (Cohen and Levinthal 1990). While internal R&D is traditionally used to proxy this capacity, in SMEs, where structured R&D activities are less frequent, employee training takes on a critical function. Due to their leaner structures, SMEs strongly depend on the skills and expertise of their owners and personnel to remain adaptive, innovative, and competitive.

Recruitment also contributes by enhancing human capital through the selection of individuals with suitable skills and backgrounds. Although challenges such as skill mismatches, information asymmetries, and recruitment costs persist, there is evidence that employees with higher levels of education positively influence a firm's ability to absorb and exploit external knowledge (Gray 2006; Oyer and Schaefer 2011).

For SMEs, therefore, targeted investment in human capital—via both training and recruitment—is not just a support function but a strategic lever to strengthen internal capabilities and unlock the potential of external knowledge.

Research and development (R&D) activities conducted within firms play a critical role in shaping both the propensity and the capacity to innovate. R&D is a key driver of technological progress, not only because of its direct contribution to firm-level innovation, but also because of its substantial potential to generate positive externalities, such as spillovers that benefit other firms, related industries, consumers, and, in some cases, society at large (Comin 2016). The literature consistently highlights R&D as a strategic asset for building internal knowledge and capabilities and for developing new products and processes that enhance efficiency and reduce costs. Technological advancements generated by R&D may also provide firms with early-mover advantages in emerging market niches or specialized segments (Segarra and Teruel 2011).

However, when considering SMEs, the dynamics of R&D adoption exhibit specific characteristics. As noted by Baumann and Kritikos (2016), micro and small enterprises are often subject to distinct drivers and barriers compared to larger firms, particularly due to the sunk-cost nature and risk profile of R&D investments.

Moreover, R&D expenditures are subject to threshold effects (Cohen and Klepper 1996), driven by decreasing marginal returns. This issue mirrors broader concerns in productivity theory about diminishing returns on capital and other firm assets (Hall and Mairesse 1995). These non-linearities are especially relevant in the context of environmental innovation (EI) and circular economy practices, where the intensity of R&D investment does not necessarily translate proportionally into innovation outcomes.

For these reasons, this study models R&D effects using a non-linear specification to account for the possibility of diminishing or even negative marginal contributions of R&D investment on firm-level innovation performance.

Drawing on this literature framework, this paper investigates the pivotal role of SMEs in advancing the circular transition through the adoption of eco-innovation. The central objective is to identify the factors influencing circular adoption, with a particular focus on the internal drivers that may shape firms' strategic decisions in this domain. In particular, research and development, environmental knowledge, education, and employee skills are conceptualized as critical resources and capabilities that enable SMEs to overcome structural barriers and to engage proactively in eco-innovative activities. Nevertheless, these factors are not expected to operate uniformly across the different dimensions of adoption.

To address this, the study considers two distinct levels of analysis. The first captures the initial decision to adopt a circular practice, representing the extensive margin of adoption. The second reflects the intensity of adoption, thereby accounting for the depth of engagement with circular practices within each innovation category.

Taken together, this framework emphasizes a dual approach: it allows us to examine not only the likelihood that SMEs adopt circular innovations but also the extent to which they intensify their adoption across multiple practices. This duality is essential for understanding the heterogeneity of eco-innovation behaviors among SMEs and provides the theoretical foundation for the empirical analysis and hypothesis testing presented in the following sections.

3 Data and methodology

3.1 The surveys

The work exploits information retrieved from two original surveys, covering 4600 Italian manufacturing firms, conducted as a panel in 2017–2018 and 2019–2020 by the University of Ferrara (CERCIS Research Centre on Circular Economy Innovation and SMEs of the Department of Economics and Management). The surveys were developed in a circular economy project, and cover four main macro-sections: firm characteristics, innovation and investment; circular economy, and organization, training, and labor relations. In particular, the surveys focused on SMEs' circular strategies through specific questions on ten innovative circular practices over two periods, i.e., new alternative solutions aimed at reducing environmental damage in a circular domain.

To the best of our knowledge, a similar wealth of information does not exist in Italy concerning the manufacturing sector and circular innovations. As previously mentioned, Italy's industrial fabric is largely characterized by SMEs, which represent the country's economic engine. For these reasons, by leveraging the data, it is possible to extrapolate circular strategies for Italian firms.

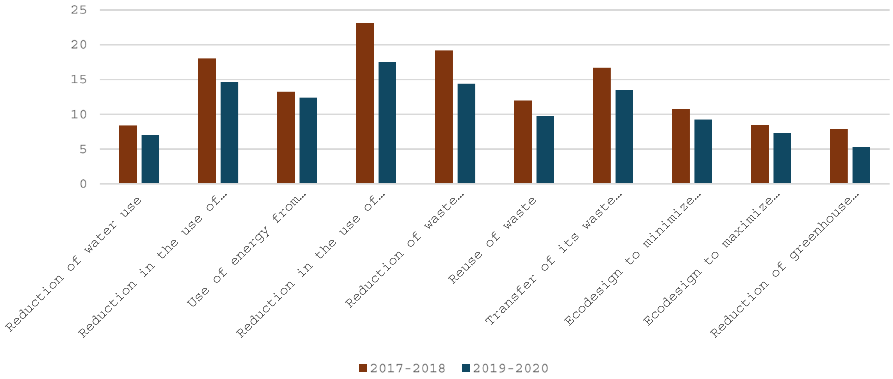

Fig. 1 Adoption rates of ten circular innovations by Italian manufacturing SMEs across two-periods (own elaboration using CERCIS data)

Figure 1 shows the adoption rate of each circular innovation across the two different periods. Of the total number of firms that responded to the survey, the main circular innovations introduced in both 2-year reference periods were aimed at reducing electricity use (23% in the first wave and 17% in the second wave) and production of waste (19% in the first wave and 14% in the second wave). Additionally, in the first reference period analyzed, innovations aimed at reducing the use of raw materials were also among the most adopted innovations (18%). From the spread of specific types of circular innovations, we see that they mainly affect the magnitude of 'reduction' and 'reuse' of resources, which appear to be the most preferred circular strategies of the firms in the surveys.

This is not the case when considering the transition from the first to the second reference period. There was a general reduction that affected the overall implementation of all the circular innovations. In the first reference period, the rate of adoption of all innovations was significantly higher than in the following 2-year period. Thus, it is reasonable to assume that the generalized decline was also due to the pandemic crisis, which significantly impacted businesses in 2020. In fact, circular innovations—like all other innovations and innovation investments—are affected by downturns in the business cycle and by negative exogenous shocks, such as the COVID-19 pandemic. Archibugi et al. (2013) demonstrated this also by analyzing a survey of innovation investment choices by European firms before and after a crisis. They observed that most firms reduced their innovation adoption at the onset of a crisis, while only a very small group saw the crisis as an opportunity to innovate.

Regarding the technological[1] intensity of innovating firms in the circular economy, Fig. 2a,b shows that the distribution of circular innovation strategies in two different periods, respectively, appears to be related to the technological intensity of the firm's sector in both reference periods, considering

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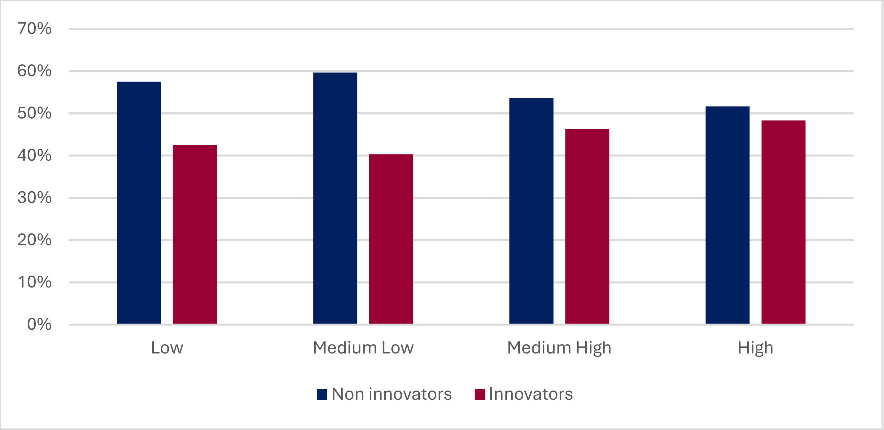
[1] For the technological intensity classification, see https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Glossary:Hightech_classification_of_manufacturing_industries.



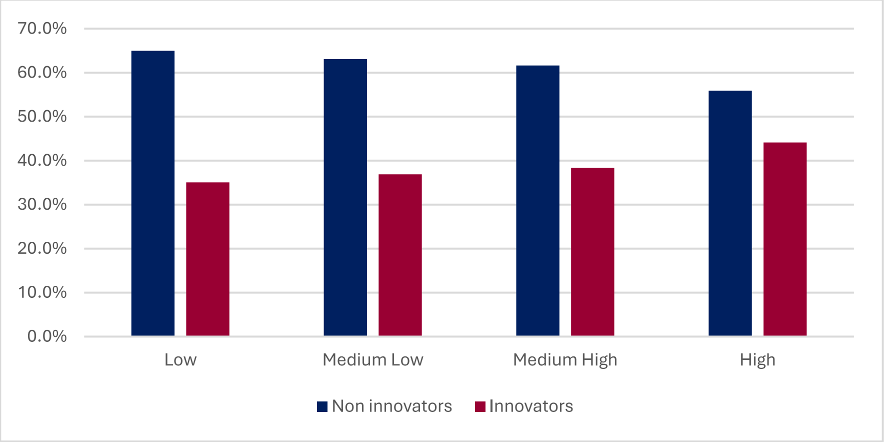


Fig. 2 **a, b** Share of innovators and non-innovators by technology intensity sector in the two periods, respectively (own elaboration using CERCIS data)

the introduction of at least one of the circular innovations mentioned. In both periods, the sample of responding firms is more concentrated in the high and medium-high technology-intensive sectors. However, interestingly enough, there is also a particular innovative activity that regards firms in low-technology-intensive sectors in the first reference period (2017–2018).

Figure 3a and b shows the data by firm size. In this case, we see a significant shift in distribution. In the first reference period, medium-sized enterprises, followed by large firms, reported greater implementation of circular innovations. In the subsequent 2-year period, this was true for only large firms. This result is particularly significant when considering the general decline caused by the pandemic, which again shows the greater resilience of large enterprises in times of crisis.

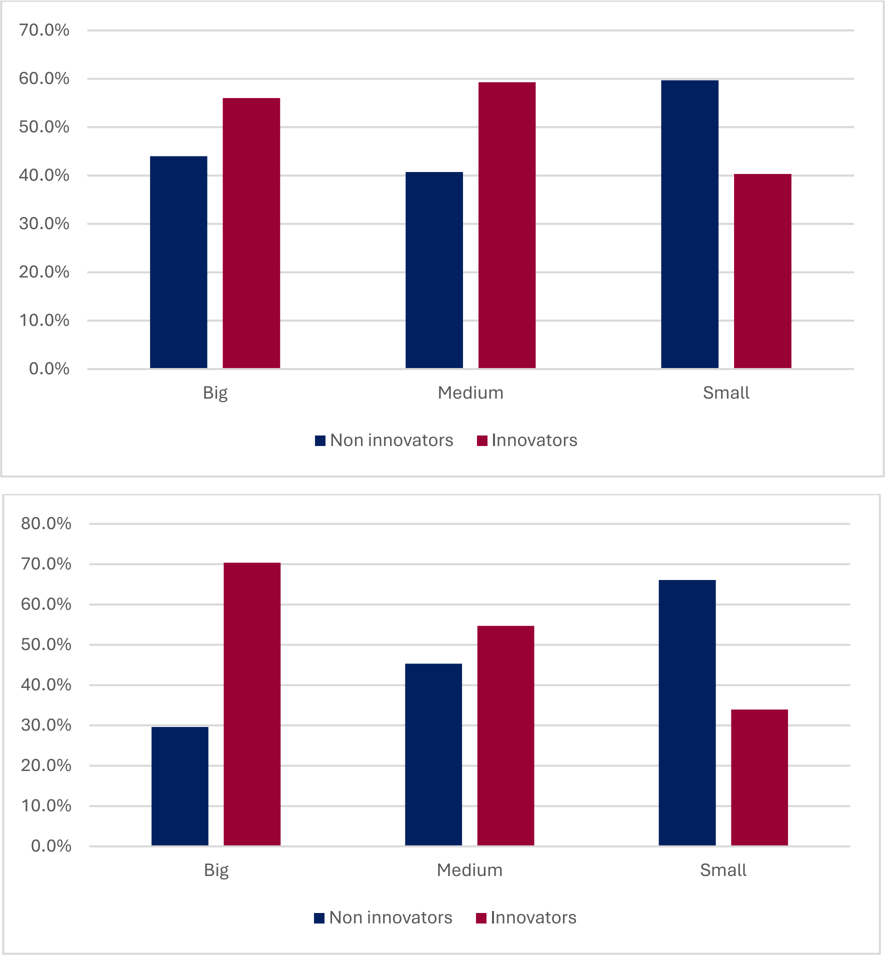


Fig. 3 a, b Share of innovators and non-innovators by size in two periods, respectively (own elaboration using CERCIS data)

4 Methods and econometric strategies

The aim of this study is to analyze the drivers of circular innovation practices related to the intrinsic characteristics of the Italian SMEs. The analysis focuses on employees, skills, and R&D investments, while also accounting for firms' export activities and sectoral affiliations. We adopted a dual approach. First, to identify the principal factors that influence the decision to adopt a circular innovation in a firm. Second, to analyze how these drivers influence the intensity of adoption of circular innovations for each of the five innovation categories.

This dual approach allows us to detect potential differences across the various types of circular innovations and to determine whether the influence of enabling factors varies by category. Understanding this heterogeneity is particularly important for shaping targeted and effective policy recommendations. The conceptual framework is illustrated in the figure below Fig. 4.

Regarding the first approach, to identify the main factors influencing a firm's decision to adopt circular innovation, we employ a Probit random-effects model. This model estimates the effect of each independent variable on the adoption decision. The dependent variable is a dummy variable taking the value of one if a specific circular innovation is adopted. By doing this, we assume that the residuals of the model and all the regressors are independent and not correlated (Wooldridge 2010). The baseline Probit specification is described in Eq. (1), using the latent expected utility model of a firm in adopting a circular innovation as in Pronti et al. (2023),

$$Y_{it}^{*} = X_{it}\beta^{*} + v_i + \varepsilon_{it}^{*} \tag{1}$$

where Y_{it}^{*} is the latent expected net utility of the *i-th* firm adopting an innovation at time t; X_{it} is a vector of covariates that explicate the level of expected utility derived by the circular innovation, composed of independent variables of interest that proxy the main factors being assessed (i.e., R&D, training, human capital) and controls that can influence the probability of adopting circular innovations (e.g., firm size, main market, sector of activity); β^{*} is a vector of parameters to be estimated, including the intercept; ε_{it}^{*} is a random error uncorrelated to the explanatory variables that follows a normal distribution with zero mean and fixed variance δ^2; and v_i represents time-invariant unobserved effects (Wooldridge 2010).

Unfortunately, the expected utility function is unobservable, and the only action that can be observed is the ex post decision of the *i-th* firm to adopt/not adopt a circular innovation. This can be modelled using a binary choice model where the dummy variable assumes positive values if the expected utility of

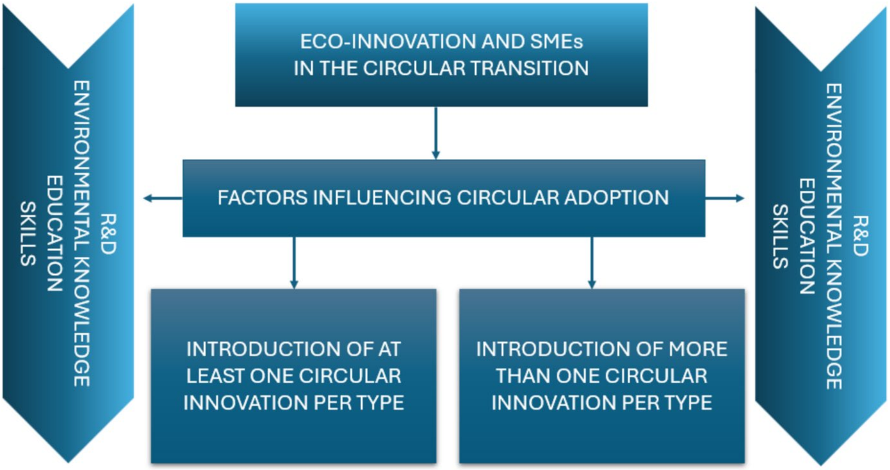


Fig. 4 Conceptual framework

the firm in adopting the circular innovation is positive ($Y_{it} = 1$ if $Y^*_{it} > 0$), otherwise, if the *i-th* firm's expected utility is negative, the dummy variable assumes a 0 value ($Y_{it} = 0$ if $Y^*_{it} \leq 0$). Following this approach, it is possible to predict the likelihood of circular innovation adoption using a Probit model as in Eq. (2).

$$Pr\left(Y_{it} = 1|X_{it}, v_i\right) = \phi\left(X_{it}, v_i\right) \tag{2}$$

where $\phi(.)$ is the distribution function of ε^*_{it} and can be approximated by a normal distribution function used to estimate the parameters of interest X_{it}. To do so, we must rely on the strict exogeneity assumption that refers to the uncorrelation between the regressors X_{it} and the error term v_i at all time periods (Wooldridge 2010).

Regarding the second approach, i.e., analyzing how these drivers influence the intensity of adoption of circular innovations per category of innovation, we employ a fixed effect Poisson model, which uses a maximum likelihood estimation technique that allows us to consider two main aspects of our data:

(1) Defining our dependent variable as a count variable since it considers the number of circular innovations adopted by each firm during the two reference periods (i.e., 2017–2018, 2019–2020);
(2) The inflation of zeros in our distribution is composed of structural zeros (i.e., firms which do not adopt innovations) and non-structural zeros (i.e., firms that could adopt but decide not to) (Hutchinson and Holtman 2005; Wooldridge 2010). Moreover, by using the Poisson model with fixed effect, we can accommodate the problem of endogeneity bias due to unobserved time-invariant heterogeneity (Wooldridge 2010).

The Poisson model estimates the expected value of a count variable using an exponential function, as shown in Eq. (3), to interpret the coefficients one must transform the model using natural logs, as shown in Eq. (4) (Wooldridge 2018).

$$E\left(X_{it}\right) = exp(\alpha_i + \sum\nolimits_{m=1}^{n} \beta X_{mit}) + \varepsilon_{it} \tag{3}$$

$$ln[E\left(X_{it}\right)] = \alpha_i + \sum\nolimits_{m=1}^{n} \beta X_{mit} + \varepsilon_{it} \tag{4}$$

where α_i is the constant term and β_{it} are the coefficients to be estimated for the vector of m independent variables X_{it}.

Wooldridge (2010) provides a more detailed explanation of the Poisson model, and its baseline specification is described in Eq. (5):

$$\Pr\left(Y_{it} = Y_{it}|X_{it}\right) = \frac{1}{y_{it}!}\exp\left\{-\exp\left(\alpha_i + X_{it}\right)\right\}\exp\left(\alpha_i + X_{it}\right)^{Y_{it}} \tag{5}$$

The effect of each independent variable can be approximated in a semi-elasticity form, with the coefficients of the independent variables interpreted as a percentage change in the dependent variable given by a unitary change of the independent variable $\%\Delta E\left(X_{it}\right) \approx (100\beta_{it})\Delta X_{it}$ (Cameron and Trivedi 2009, 2013). Both the Probit and the Poisson models use robust standard errors.

Considering that the Poisson regression is not linear, the marginal effects (MEs) of continuous regressors cannot be directly extrapolated using the estimated coefficients, as occurs when using OLS, since the unit change of each regressor has an effect on the conditional mean but depends on the point at which the regressor is measured. As explained by Cameron and Trivedi (2009)

$$ME = \frac{\partial E[y|x]}{\partial x_j} = \beta_j \exp(x\prime\beta) \tag{6}$$

The ME of an infinitesimal change of x_j on the count variable Y depends on the level assumed by X_j and by the values of the other regressors. Therefore, to consider the MEs, additional computations are required. One is the average marginal effect (AME) defined by Cameron and Trivedi (2013) as:

$$AME_j = \frac{1}{n}\sum_{i=1}^{n}\frac{\partial[y_i|X_i]}{\partial X_{ij}} = \frac{1}{n}\sum_{i=1}^{n}\beta_j \exp(X\prime_i\beta) = \beta_j\bar{y} \tag{7}$$

Thus, by using the AME, it is possible to overcome the problem of each individual observation having its own ME. This is done by estimating the typical value by aggregating over all individuals and calculating the average response (Cameron and Trivedi 2013; Long and Freese 2001).

4.1 Data

In the following subsections, we describe the main variables used in the econometric analysis. The descriptive statistics are shown in Table 1. We used the raw data from the mentioned surveys. We checked the data and excluded outliers that presented structural problems ascribable to compiling errors or mistakes in responses (e.g., the number of innovations was requested as an open answer, and some respondents recorded improbable values with many zeros). After controlling for data errors, we created a balanced panel and only considered firms that were present in both waves. It was decided to consider the possibility of using fixed effect models in the innovation intensity model (Poisson). Even though this could be seen as a disadvantage by reducing the overall sample, the validity and robustness of the estimation increased substantially because we could control for unobserved heterogeneity, thereby reducing endogeneity problems. Our final panel sample consisted of 4578 firms, observed over the two survey periods (the initial unbalanced sample comprised 9213 observations).

4.1.1 The dependent variables

Circular innovations are those innovations that the firms had declared to have adopted during the two reference periods (i.e., 2017–2018, 2019–2020). All

Table 1 Descriptive statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Waste reduction (dummy)	4578	.272	.445	0	1
Materials (dummy)	4578	.155	.362	0	1
Design (dummy)	4578	.125	.331	0	1
Energy (dummy)	4578	.245	.43	0	1
Pollution (dummy)	4578	.018	.134	0	1
Waste reduction (countable)	4578	.685	2.151	0	47
Materials (countable)	4578	.309	1.445	0	30
Design (countable)	4578	.397	1.864	0	31
Energy (countable)	4578	.5	1.691	0	30
Pollution (countable)	4578	.218	1.257	0	40
WorkersRD (%)	4578	3.338	10.69	0	100
Graduated (%)	4578	3.57	9.972	0	100
RDExpenditure (% of Revenues)	4577	2.512	7.14	0	82.5
Env_Knowledge (dummy)	4578	.037	.189	0	1
Training_Intensity (hours per employee)	4578	1.938	9.034	0	384.615
Year 2018	4578	.5	.5	0	1
Year 2019	4578	.5	.5	0	1
Exporter	4578	.461	.499	0	1
Group	4578	.112	.316	0	1
Age	4578	29.655	21.348	0	221
Micro	4578	.11	.313	0	1
Big	4578	.01	.101	0	1
Head abroad	4578	.029	.167	0	1

interventions were considered as innovations without distinguishing between technological, organizational, process changes, or changes to the company's main business model. Moreover, all changes that occurred and were declared by the firm to be related to circularity were also considered innovations. With this approach, both radical and incremental innovations were considered equally. The questionnaire, although it explored the scope of innovation, did not investigate the type of innovation in terms of radicalness. For this reason, we are unable to make a vertical distinction and have made only a horizontal one with respect to the different types of innovation. The difficulty in including this aspect in the questionnaire is mainly due to the level of discretion that would have been left to the respondent in defining the radicalness of the innovation introduced.

We divided circular innovations into five macro categories to obtain homogeneous descriptions of the strategies firms use to achieve circularity. Distinguishing between different types of innovation can be extremely important, as it allows for accounting for the high degree of heterogeneity among them. This may be due to the inherently different nature of the innovations, since the motivations and drivers for adopting improvements in a firm's circularity can vary widely depending on the business strategy adopted to improve the firm's internal sustainability process (such as energy savings, waste reduction, or product design). The categorization developed by Guerreschi and Zecca (2025) aims to look at circular innovations by considering the entire life cycle—from material use reduction, to design, and finally to the reduction of waste and pollution in general. This choice therefore allows us to follow the activities of firms both in the input and output phases (Chioatto et al. 2024).

The first category of innovations refers to waste reduction innovations (*Waste reduction*), which includes the following circular interventions and strategies:

(i) Reduction of waste emissions,
(ii) Reuse of waste as secondary materials in the productive cycle, and
(iii) Transferring waste to other firms to be used as secondary materials in their internal productive cycle.

The second category of circular innovations refers to all circular interventions and strategies aimed at reducing the materials used (*Material innovations*) within the firm's production cycles, as well as the reduction of raw materials in the production process. This category does not include energy, which is in a category of its own, given its crucial role in production and its susceptibility to specific policies.

The third category refers to design innovations (*Design innovations*). It includes all the interventions and strategies adopted by the firm to reduce environmental impact at the beginning of the production cycle, by re-inventing the way raw materials and semifinished products are combined and processed in order to reduce the generation of waste. This category includes the following circular strategies:

(i) Innovations aimed at minimizing the use of raw materials, and
(ii) Innovations aimed at maximizing the recyclability of materials (either by-products or core-products).

The fourth category regards innovations in the energy field (*Energy innovations*). These include all the innovations:

(i) Adopted by the firm to reduce energy consumption and,
(ii) Aimed at increasing the use of renewable energy in the firm's internal process, both production and consumption.

The fifth category aimed at reducing the firm's environmental impact (*Pollution reduction innovations*); those include innovations to reduce:

(i) Greenhouse gas emissions, and
(ii) Water pollution.

To accommodate our dual strategy (i.e., adoption drivers and intensity of adoption drivers), we employed two types of dependent variables. As previously noted, for the Probit model, we employ dummy variables as dependent variables, whereas for the Poisson model, we employ count variables. The dummy variables assume the value of 1 if a firm has adopted at least one innovation in at least one of the five innovation categories. The count variables assume a value equal to the number of innovations adopted by the firm for each innovation category. In the latter case, a firm can adopt various types of innovations included in the same macro-category of circular innovations.

4.1.2 The independent variables

In our analysis, we focus on employee training, human capital, research activities, and management's pro-environmental attitude as specific aspects affecting the circular innovation strategies of SMEs. These aspects have already been highlighted as potentially important drivers of sustainable and circular innovation in a previous study on micro firms (Pronti et al. 2024).

As main independent variables linked to research and development (R&D) activities, we chose the percentage of workers involved in R&D (*WorkersRD*) and the percentage of R&D expenditure over the firm's total revenues (*RDExpenditure*). This last variable is also considered in its quadratic form (*RDExpenditure2*) to capture all the potential non-linearities which can describe negative marginal productivity of R&D investments as described in Sect. 2. To consider human capital, we use the percentage of workers who graduated from university (*Graduated*) over total employees. Lastly, employee training is considered by using the intensity of worker training measured as hours of training per employee (*Training_Intensity*).

Moreover, we used a dummy variable as a proxy for management's pro-environmental knowledge (*Env_Knowledge*). This dummy variable assumes a value equal to one if the respondent correctly answers two specific questions related to environmental sustainability. The first is a multiple-choice question and requires knowledge of the range of ETS values in the 6 months prior to the survey. The second is a Yes/No question related to the knowledge of the term "ecosystem service". If the respondent answers the first question correctly and "yes" to the second question, the variable *Env_Knowledge* assumes the value of 1, if not the value is 0. By doing this, we can proxy the respondents' knowledge (who, most of the time, are part of management or are staff close to management) in two specific fields of sustainability, thus providing us with a general idea of management's environmental knowledge and its influence on circular innovation strategies.

We also include additional controls to reduce 'omitted variables biases' and to improve the robustness of our results, however, we decided to choose a parsimonious specification of the econometric model to avoid over-specification. Following Pronti et al. (2024) and Cainelli et al. (2020), we included specific dummies as controls.

The first set of dummies controls for structural differences and heterogeneity that may affect firms' circular innovation strategies. The following variables take the value of 1: *Exporter* if the firm exports products abroad; *Group* if the firm is part of a corporate group, and *Head_Abroad* if the firm's corporate headquarters are outside of Italy. We also consider firm size in terms of workers employed. The variable *Micro* takes the value of 1 if the firm has fewer than ten employees, and *Big* takes the value of 1 if the firm has more than 200 employees. Finally, we control for how long the firm has been in existence (*Age*) measured in years, to consider if this aspect can affect circular innovation strategies. Moreover, to control for exogenous common idiosyncratic shocks, we employ a time dummy for the second wave.

Finally, we create a factor variable to control for the structural heterogeneity of the firm's operating sector, since it can significantly impact its circular innovation strategies. This variable considers the different specialization sectors of the firm. We codified the ATECO sector, which is a specific identification code by sector of activity used for the fiscal identification of a firm. Our data identifies 55 different sectors of activity.

5 Results

The results of our analysis, using the Probit model, are shown in Table 2, whereas the results of the Poisson model are shown in Table 3. In both tables, the results presented from column 1 to column 5 are respectively for waste reduction innovations, materials innovations, design innovations, energy innovations, and pollution reduction innovations. In the table with the results of the Poisson model (Table 3), the results are displayed considering two specifications (without and with the quadratic term of R&D expenditure).

5.1 The decision to adopt circular innovations (Probit model)

The first analysis using the Probit model (Table 2) focuses on the drivers of circular innovation adoption linked to the decision to adopt at least one innovation. As expected, we found that the factors influencing circular innovation adoption decisions are heterogeneous among different types of firms. For Waste reduction innovations (column 1) the main drivers of adoption are the level of expenditure in R&D activities as a percentage of total revenues (*RDExpenditure*) and environmental knowledge (*Env_Knowledge*) by management, both with a positive coefficient and 99% statistical significance. Training intensity is also positive, but with lower statistical significance (90%).

These factors are important drivers of adoption also for material reduction innovations (column 2), even if in this case the training intensity shows a slightly higher level of statistical significance (95%). In this case, we also see the percentage of workers employed in R&D activities as an additional factor influencing innovation adoption, with a statistical significance of 99%.

For innovations linked to product design (column 3), which include changes in the design to reduce waste, use of material, and improve recyclability, expenditure in R&D (*RDExpenditure*) is confirmed as a positive driver of adoption with a statistical significance of 99%. In this case, human capital, proxied as the percentage of graduated workers, shows a positive effect as a driver of design innovation, also with a statistical significance level of 99%.

Considering Energy innovations (column 4) focused on the reduction of energy intensity and increased use of renewable sources, the main adoption drivers are the

Table 2 Results of the Probit models

	(1)	(2)	(3)	(4)	(5)
Variable	Model 1 Probit RE - Waste Reduction innovations-	Model 2 Probit RE - Materials innovations-	Model 3 Probit RE - Design innovations-	Model 4 Probit RE - Energy innovations-	Model 5 Probit RE - Pollution reduction innovations-
WorkersRD (%)	0.00502	0.00803**	0.00592	0.00411	0.0114**
	(1.456)	(2.468)	(1.626)	(1.349)	(2.008)
Graduated (%)	0.00257	0.00389	0.0113***	0.00753**	0.00278
	(0.761)	(1.040)	(3.176)	(2.283)	(0.414)
RDExpenditure (% of Revenues)	0.0256***	0.0221***	0.0266***	0.00928**	0.0183**
	(5.193)	(4.188)	(5.031)	(1.995)	(2.388)
Env_Knowledge (dummy)	0.566***	0.633***	0.168	0.394**	0.594**
	(3.360)	(3.811)	(0.854)	(2.474)	(2.067)
Training_Intensity (hours per employee)	0.00542*	0.00886**	0.00241	– 1.87e-05	0.00207
	(1.839)	(2.427)	(0.700)	(– 0.00709)	(0.629)
Exporter	0.367***	0.315***	0.581***	0.276***	– 0.0367
	(4.647)	(3.772)	(6.404)	(3.683)	(– 0.229)
Group	0.0665	0.311**	0.142	0.162	0.114
	(0.498)	(2.317)	(0.982)	(1.257)	(0.434)
Age	0.00474***	0.00400**	0.00393**	0.00580***	0.00576**
	(2.702)	(2.212)	(2.095)	(3.194)	(1.988)
Micro	– 0.164	– 0.176	– 0.0333	– 0.157	– 0.119
	(– 1.460)	(– 1.417)	(– 0.249)	(– 1.471)	(– 0.438)
Big	0.795**	0.426	0.192	0.744***	1.119**
	(2.427)	(1.342)	(0.510)	(2.612)	(2.154)
Head_Abroad	0.00223	– 0.123	– 0.105	– 0.0460	– 0.182
	(0.00825)	(– 0.442)	(– 0.379)	(– 0.179)	(– 0.387)

Table 2 (continued)

	(1)	(2)	(3)	(4)	(5)
Constant	– 1.352***	– 1.894***	– 2.286***	– 1.311***	– 3.205***
	(– 9.459)	(– 11.37)	(– 12.41)	(– 9.223)	(– 8.117)
Observations	4,580	4,566	4,534	4,576	4,427
Number of ID	2,302	2,301	2,298	2,303	2,258
Robust	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID
Year FE	YES	YES	YES	YES	YES
Ind FE	NO	NO	NO	NO	NO

Other Controls: Ateco sector

Robust z-statistics in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3 Results of the Poisson models

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variable	Model 1.1 Poisson FE - Waste Reduction innovations-	Model 1.2 Poisson FE - Waste Reduction innovations RD quadratic-	Model 2.1 Poisson FE - Materials innovations-	Model 2.2 Poisson FE - Materials innovations RD quadratic-	Model 3.1 Poisson FE - Design innovations-	Model 3.2 Poisson FE - Design innovations RD quadratic-	Model 4.1 Poisson FE - Energy innovations-	Model 4.2 Poisson FE - Energy innovations RD quadratic-	Model 5.1 Poisson FE - Pollution Reduction innovations-	Model 5.2 Poisson FE - Pollution Reduction innovations RD quadratic-
WorkersRD	0.0148**	0.0147**	0.0185***	0.0191***	– 0.00320	– 0.00474	0.00892*	0.00876*	0.0242**	0.0236**
	(2.370)	(2.370)	(2.899)	(2.801)	(– 0.391)	(– 0.609)	(1.878)	(1.831)	(1.988)	(1.977)
Graduated	0.00705	0.00747	– 0.00450	– 0.00430	0.0182**	0.0206**	0.00234	0.00331	0.0110	0.0120
	(1.106)	(1.150)	(– 1.048)	(– 0.970)	(1.991)	(2.205)	(0.374)	(0.527)	(0.962)	(1.050)
RDExpenditure	0.0169*	0.0397**	– 0.00354	0.0398**	0.00491	0.0502**	– 0.00671	0.0312	– 0.00580	0.00843
	(1.897)	(2.397)	(– 0.318)	(1.986)	(0.507)	(2.348)	(– 0.844)	(1.492)	(– 0.455)	(0.376)
RDExpenditure2		– 0.000560*		– 0.000976**		– 0.00107**		– 0.000779*		– 0.000306
		(– 1.701)		(– 1.980)		(– 2.331)		(– 1.759)		(– 0.676)
Env_Knowledge	0.224	0.253	– 0.189	– 0.148	– 0.0703	– 0.0787	0.169	0.216	– 0.418	– 0.410
	(1.324)	(1.519)	(– 0.678)	(– 0.556)	(– 0.186)	(– 0.208)	(0.705)	(0.915)	(– 1.018)	(– 1.003)
Training_ Intensity	0.00478	0.00453	0.0156***	0.0135***	0.000806	– 0.00148	0.0106**	0.00907**	0.0142***	0.0134***
	(1.475)	(1.413)	(4.266)	(4.120)	(0.173)	(– 0.343)	(2.299)	(2.216)	(3.307)	(3.101)
Exporter	0.0354	0.0276	– 0.229	– 0.207	0.164	0.172	– 0.234	– 0.251	– 0.0147	– 0.0145
	(0.135)	(0.105)	(– 0.691)	(– 0.650)	(0.488)	(0.513)	(– 1.412)	(– 1.517)	(– 0.0377)	(– 0.0371)
Group	– 0.158	– 0.122	– 0.705	– 0.636	0.939***	0.882***	0.521	0.542	– 0.336	– 0.329
	(– 0.454)	(– 0.373)	(– 1.335)	(– 1.322)	(3.216)	(3.009)	(1.355)	(1.343)	(– 0.842)	(– 0.826)

Table 3 (continued)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Age	0.0142**	0.0139**	0.00568	0.00607	0.00299	0.00332	0.0117*	0.0113*	0.0169**	0.0168**
	(2.509)	(2.464)	(0.869)	(0.996)	(0.346)	(0.395)	(1.842)	(1.788)	(1.994)	(1.994)
Micro	– 0.160	– 0.158	0.0145	0.00996	0.563	0.609*	0.266	0.333	0.0841	0.0981
	(– 0.615)	(– 0.612)	(0.0470)	(0.0319)	(1.565)	(1.700)	(1.121)	(1.383)	(0.208)	(0.240)
Big	2.134***	2.129***	0.669	0.624	2.398*	2.171	15.64***	15.66***	15.19***	15.10***
	(4.943)	(4.966)	(0.728)	(0.677)	(1.726)	(1.498)	(19.51)	(19.70)	(11.39)	(10.97)
Head_ Abroad	0.600	1.747**	– 15.75***	– 14.10***	– 0.706	2.119	– 15.49***	– 14.86***	– 0.418	0.0293
	(1.463)	(2.294)	(– 14.36)	(– 7.607)	(– 0.441)	(0.829)	(– 23.47)	(– 16.71)	(– 0.305)	(0.0160)
Robust	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Other Controls:	Ateco Sector									
Observations	1760	1760	1076	1076	872	872	1638	1638	800	800
Number of ID	880	880	538	538	436	436	819	819	400	400
Robust	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Robust z-statistics in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

share of graduated workers (*Graduated*), R&D expenditure (*RDExpenditure*), and environmental knowledge (*Env_Knowledge*), all with a statistical significance level of 95%.

Finally, for innovations aimed at impact reduction in terms of GHG emissions and water pollution (column 5), the main determinants of adoption are the share of workers involved in R&D activities (*WorkersRD*), the firm' expenditure in R&D activities (*RDExpenditure*), and management's environmental knowledge (*Env_Knowledge*) all with a statistical significance level of 95%.

For the Probit model, the controls that seem to be factors influencing circular innovation adoption decisions are mainly being an exporting firm (*Exporter*), which was found to have a positive statistical significance (99%) coefficient for waste reduction, material reduction, design, and energy innovations. The other control variable with a statistical effect on innovation decisions is the age of the firm (*Age*), suggesting that older firms have a higher propensity to adopt circular and eco-innovations than younger firms. The dummy indicating large firms (*Big*) is statistically significant only for waste reduction (95%), energy (99%), and pollution reduction (95%) innovations.

5.2 The intensity of circular innovation adoption (Poisson model)

The second analysis employs a Poisson model (Table 3) to examine the factors influencing the intensity of circular innovation adoption, measured as the count of circular innovations adopted within distinct categories. The results are shown for two different specifications for each dependent variable considered: using R&D in a linear and non-linear approach by considering its quadratic term. Since the Poisson model is estimated by using an exponential function; the coefficients should be interpreted on the log scale. Therefore, a unitary change in the estimated β coefficients represents the expected change in the dependent variable by e^{β} units holding all other variables constant (Cameron and Trivedi 2013). In other words, we can interpret the Poisson regression coefficients as the difference in the logs of the expected count variable due to a change in the regressor, holding all other variables constant (Wooldridge 2010). This can be translated as the percentage change in the dependent variable due to a unitary change of the independent variable or as semi-elasticity (Cameron and Trivedi 2013; Long and Freese 2001).

The results of the Poisson model are not straightforward to interpret. Therefore, to consider the main impacts of the independent variables regarding the number of circular innovations adopted, Table 4 presents the results in terms of incidence rate ratios (IRR).[2] IRRs are simply the exponentiated value of the regression coefficient function (Wooldridge 2010). An IRR can be interpreted as the multiplicative increase in the rate of the dependent variable due to a change in the independent variable (i.e., a unitary change for numeric variables and a change of state for dummies). It is calculated by taking the difference between the IRR and 1, e.g., if

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[2] The IRR is calculated as $\exp(\beta)$ for each variable (Cameron and Trivedi 2013).

Table 4 Incidence rate ratios (IRR) of the Poisson models

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variable	IRR Model 1 Poisson FE - Waste Reduction innovations-	IRR Model 1.1 Poisson FE - Waste Reduction innovations R&D quadratic-	IRR Model 2 Poisson FE - Materials innovations-	IRR Model 2.2 Poisson FE - Materials innovations R&D quadratic-	IRR Model 3 Poisson FE - Design innovations-	IRR Model 3.1 Poisson FE - Design innovations R&D quadratic-	IRR Model 4 Poisson FE - Energy innovations-	IRR Model 4.1 Poisson FE - Energy innovations R&D quadratic-	IRR Model 5 Poisson FE - Pollution Reduction innovations-	IRR Model 5.1 Poisson FE - Pollution Reduction innovations R&D quadratic-
Workers RD	1.015**	1.015**	1.019***	1.019***	0.997	0.995	1.009*	1.009*	1.025**	1.024**
Graduated	1.007	1.007	0.996	0.996	1.018**	1.021**	1.002	1.003	1.011	1.012
RD Expenditure	1.017*	1.041**	0.996	1.041**	1.005	1.051**	0.993	1.032	0.994	1.008
RD Expenditure2		0.999*		0.999**		0.999**		0.999*		1.000
RD Expenditure (at means)		**1.04258**		**1.04327**		**1.05617**		**1.03394**		**1.00924**
Env Knowledge	1.251	1.288	0.828	0.862	0.932	0.924	1.184	1.242	0.659	0.663
Training Intensity	1.005	1.005	1.016***	1.014***	1.001	0.999	1.011**	1.009**	1.014***	1.013***
Observations	1760	1760	1076	1076	872	872	1638	1638	800	800
Number of ID	880	880	538	538	436	436	819	819	400	400
Robust	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID	Cluster ID
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Robust z-statistics in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

a dummy variable shows an IRR of 1.25 it means that the category codified by the variable 1 increases the adoption of a specific innovation by 25%. If a numeric variable shows an IRR of 1.03, it means that a firm with one unit extra of that variable increases the intensity of adoption by 3% more than a firm with one unit less of that variable (Wooldridge 2010).

Once again, the regression results highlight considerable heterogeneity, and distinct factors are associated with the adoption of different types of circular innovations. Considering waste reduction innovations and starting from the results in their direct form (Table 3, column 1), the factor that affect intensity of adoption the most is R&D. The variables that influence the number of waste innovation adoptions are the percentage of workers involved in R&D activities as a share of overall workers, and the level of R&D investments as a share of revenues (*RDExpenditure*). Both have a 99% and 90% statistical significance level, respectively. To determine the impact of the two variables mentioned, we can consider the IRRs shown in Table 4. The expected delta in the dependent variable, due to a unitary change of the regressors, is calculated by subtracting the IRR from 1. Therefore, for waste reduction, a change of 1% in the number of workers employed in R&D increases the expected number of waste innovations adopted by 1.5% (Table 4, column 1). Similarly, a 1% increase in total revenues invested in R&D increases the expected number of waste reduction innovations by 1.7% (Table 4, column 1).

For material use innovations (Table 3, column 3), the main factors influencing adoption intensity is again R&D (the variable proxying human capital involved in R&D activities (*WorkersRD*) is a positive coefficient and a statistical significance level of 99%). Similarly, investment in training for employees seems to be a positive driver of innovation, with a statistical significance level of 99% also in this case. These two variables increase the expected number of material innovations, respectively by 1.9% and 1.6%, per unitary change in the level of the regressor holding everything as constant (Table 4, column 3).

When considering design innovations (Table 3, column 5), the only statistically significant variable is the measure of human capital: the share of graduated employees of the total workforce, with a slightly lower statistical significance (90%). In terms of impacts, the share of graduated workers of the total workforce can increase the expected number of innovations adopted by 1.8% units for each 1% increase of graduated workers employed by the firm (Table 4, column 5).

Regarding energy innovations (Table 3, column 7), the percentage of workers employed in R&D activities (*WorkersRD*) has limited statistical significance (90%), while investments in training activities, measured in terms of training hours per employee (*Training_Intensity*) is a positive driver of adoption intensity with a statistical significance level of 95%. The former variable increases the number of expected energy innovations adopted by 0.9% for each additional percentage of workers involved in R&D activities. Whereas the latter increases the number of expected units of energy innovation by 1.1% for each additional hour of training per employee (Table 4, column 5).

Finally, in the case of pollution reduction innovations (Table 3, column 9), the main factors that incentivize adoption intensity are again the share of workers involved in R&D activities (*WorkersRD*) and employee training

(*Training_Intensity*). The former has a statistical significance level of 95% and the latter of 99%. In terms of impact, each unitary percentage of workers involved in R&D activities increases the expected amount of pollution reduction innovations by 2.4%. Each additional hour of training per employee increases the expected number of pollution reduction innovations by 1.3% (Table 4, column 9).

As for the control variables, the firm's age (*Age*) and size seem to be the most important drivers of adoption intensity. Age has positive, statistically significant levels for waste reduction (99%), energy (90%), and pollution reduction innovation (95%). Operating as a large firm (*Big*) is a driver of adoption for waste reduction, energy, and pollution reduction innovations, each with 99% statistical significance. Being part of a corporate holding (*Group*) is positive and statistically significant (95%) only for design innovations. Conversely, having a headquarters abroad (*Head_Abroad*) reduces innovation intensity for materials and energy innovations, both with 99% statistical significance.

When considering the second specification used in the model with the quadratic term for R&D, hence assuming that R&D has a negative marginal contribution in the innovation process of firms, the results obtained are slightly different, revealing some interesting implications. The main results in terms of R&D personnel, training intensity, and the controls found in the first specification remain stable, highlighting the model's robustness. What changes is the contribution of R&D investments to the firm's innovation process, supporting our initial intuition: the marginal contribution of R&D in the intensity of the adoption innovation process is negative (i.e., its quadratic term is negative). This means that the marginal benefits of R&D in terms of innovation adoption are non-linear with an inverted U-shape relationship. Another important finding is that this pattern applies only to circular innovations, which present estimated coefficients with 95% statistical significance (only the quadratic term of waste reduction innovations is 90% statistically significant); whereas neither a non-linear nor a linear relationship with R&D investments is evident for other types of innovation (i.e., energy and pollution reduction).

As noted by Cameron and Trivedi (2013), the inclusion of a quadratic term implies that the marginal effect of the associated variable is a function of its own level. Accordingly, the marginal effect is typically evaluated at the sample mean of the variable, computed over the set of observations used in the estimation (even though other potential methods are available). The following calculations are a slight modification of Eq. (7):

$$ify = \beta_0 + \beta_1 x_1 + \beta_2 {x_1}^2 \rightarrow \frac{\partial E[y|x]}{\partial x} \frac{1}{E[y|x]} = \left(\beta_1 + 2\beta_2 x_1\right) \rightarrow AME\left(x_1\right) = (\beta_1 - 2\beta_2 \times \overline{x_1})$$

where β_1 and β_2 are the coefficients of the linear and the quadratic parameter x_1 (in our case, R&D expenditures) and $\overline{x_1}$ is the mean value of the observations considered in the regression. In this context, the AMEs of the variable *RDExpenditure* are 0.04170, 0.04236, and 0.05465 for circular innovations related to waste reduction, materials and design innovations, whereas for energy and pollution reduction innovations, the AMEs are 0.03337 and 0.00919 (not statistically significant).

In the Poisson model, the coefficients are interpreted as semi-elasticities. Therefore, the IRR can be computed based on the total marginal effect of R&D expenditures (*RDExpenditure*) evaluated at the sample means of the covariates, as previously shown.

The total marginal effect of R&D expenditure on circular innovations is estimated at 4.26%, 4.33%, and 5.62% for waste reduction, materials reduction, and design innovations, respectively. This means that a 1% increase of the firm's total expenditure dedicated to R&D; i.e., an increase in R&D intensity, leads, on average, to a 4.26% increase in the adoption of waste-related innovations, a 4.33% increase for materials-related innovations, and a 5.62% increase for design-related innovations. These effects are all statistically significant. In contrast, the semi-elasticity of R&D expenditure, with respect to the adoption of energy and pollution reduction innovations, is lower—3.39% and 0.92%, respectively—and not statistically significant.

6 Discussion

The analysis, conducted to identify the innovation drivers of various circular innovation practices among Italian SMEs over two periods, provides insights into their development dynamics. It also helps identify differences and similarities that can guide the design of policy tools specifically targeting different aspects of circularity.

Interestingly, the first notable result is that despite common traits across various innovative practices, a certain level of heterogeneity exists, affecting some of the drivers analyzed with respect to different innovation categories. The empirical evidence presented in this study highlights the multifaceted and differentiated nature of the factors driving circular innovation among Italian SMEs. As the literature has already addressed (De Marchi 2012), one of the most salient findings is the central role played by R&D (both investments and specialized employees) in fostering the adoption of various types of circular innovation. Specifically, in the first model—focused on innovation adoption—R&D investments are positively and significantly associated with all innovation categories, suggesting that such expenditures constitute a foundational requirement for initiating the transition toward eco-innovation.

However, this effect fades in the second model, which focuses on innovation intensity. This dynamic indicates that while R&D acts as a catalyst in the early stages of innovation, its marginal contribution decreases as firms consolidate their position as innovators. This has important implications for the temporal dimension of innovation policy: while upfront support for R&D is essential, long-term innovation trajectories may require different types of enablers. This condition was evidenced through a quadratic Poisson specification, indicating that R&D intensity has a diminishing marginal effect, following an inverted U-shaped relationship with innovation output. This is a particularly interesting result, as it remains relatively underexplored in the existing literature and may offer valuable insights for other empirical applications in the field of innovation and productivity analysis.

Conversely, the effect of R&D personnel is apparently also stable in the relationship with the intensity of innovation adoption (Poisson model). Notably, this non-linear relationship emerges only in the case of circular innovations such as waste reduction, material, and design-related innovations, while it does not appear to hold for innovations targeting energy efficiency or pollution reduction. A possible explanation is that circular innovations often require more complex organizational changes and higher levels of experimentation, which may initially benefit from increased R&D efforts, but face diminishing returns beyond a certain threshold. In contrast, energy and pollution reduction measures may rely on more standardized, mature technologies that exhibit more linear patterns of adoption with respect to R&D intensity. These results resonate with earlier contributions emphasizing the central role of R&D in eco-innovation adoption (Horbach 2008; Triguero et al. 2013). In particular, the inverted U-shaped effect of R&D intensity complements findings by Cainelli et al. (2015), who argue that absorptive capacity is crucial but subject to diminishing returns in later innovation stages. Our evidence thus aligns with the view that while R&D creates the conditions for early adoption, long-term trajectories rely more on organizational routines and external linkages.

Human capital also emerges as a critical component in the innovation process. The presence of university graduates, in particular, proves to be a significant driver for design-related innovations in both models. This reinforces the idea that higher levels of formal education among employees are particularly relevant in the early conceptual stages of circular innovation, where creativity, technical knowledge, and problem-solving capabilities are required. This result is consistent with expectations, as the design stage lies at the very beginning of the production process—where product conceptualization occurs—and typically demands advanced technical and creative competencies. The need for specialized and educated workers appears particularly relevant for fostering innovation in this upstream phase, reinforcing the idea that human capital is a critical enabler of circular design strategies. Complementarily, firm-managed training activities have a robust impact, especially in enhancing the intensity of innovation adoption in domains related to material use, energy efficiency, and pollution reduction. These findings suggest that SMEs investing in internal capacity building are more likely not only to innovate but also to sustain innovation over time, underlining the strategic importance of human capital development as a lever for circular transition. What emerges is a role of human capital that echoes the insights of Rennings (2000), who emphasized knowledge as a core determinant of eco-innovation, and corroborates more recent analyses highlighting the importance of specialized skills in circular design (Rizos et al. 2016). The emphasis on training also aligns with findings by Demirel and Kesidou (2011), who showed that firm-specific investments in learning activities enhance the persistence of eco-innovations over time.

This evidence also underscores the fact that different types of circular innovations may rely on different enabling factors. Design-related innovations, in particular, appear more dependent on internal knowledge and technical expertise, while other types may be more strongly influenced by other drivers, which can be internal (i.e., cost reduction) or external (e.g., supply chain integration and regulation). Recognizing this heterogeneity is crucial for both academic research and policy design, as it suggests that a one-size-fits-all approach to supporting circular innovation may be ineffective.

We expected environmental knowledge, interpreted as the presence of environmentally engaged and informed management within the firm, to exert a significantly positive influence on the adoption of circular innovations. This expectation was confirmed for all innovation types, except for those related to product design. This exception, together with the overall pattern observed, suggests that a green managerial vision alone is not the primary driver of circular innovation. Instead, firms appear to respond more strongly to external economic incentives, such as cost savings, input efficiency, and competitive advantages linked to green market positioning. This is further supported by the results of the Poisson model: in the second specification, which focuses on innovation intensity, environmental knowledge becomes statistically insignificant across all innovation types. This indicates that managerial awareness may play a role in initiating change, but sustained engagement in circular innovation is likely driven by tangible economic and strategic benefits.

Firm size consistently emerges as a key structural determinant of both innovation adoption and intensity. Larger enterprises (>200 employees) are significantly more engaged in circular practices than micro (<10 employees) or small firms, particularly in areas such as energy efficiency, pollution reduction, and waste management, which might be the innovation sector where higher gains are present in terms of cost savings due to innovation. This highlights how size matters in terms of ecological and circular transition for small and micro enterprises, which have much less potential in experimentation, sustaining R&D activities, and bearing the risks associated with innovations. Big firms are more innovation-oriented. This may be related to their greater financial resources and more developed economic structures, which better equip them to absorb losses from failures in the innovation process.

One plausible explanation for this pattern lies in the varying degrees of external environmental scrutiny to which firms are subject, depending on their size. Larger companies often operate under stricter regulatory oversight and are more exposed to environmental audits, public attention, and stakeholder pressure. Moreover, they tend to be more visible to consumers and investors, who increasingly demand transparency and environmental responsibility. As such, these firms are not only encouraged—but in many cases compelled—to innovate in order to comply with regulatory standards and maintain their reputation in the marketplace. This institutional and market-driven pressure contributes to creating a more innovation-conducive environment, particularly in areas aligned with sustainability and circular economy objectives.

These dynamics also carry clear policy implications. If growth and scale enhance a firm's capacity and motivation to engage in sustainable innovation, then developing policies to scale up smaller enterprises—through clustering, financial instruments, or capacity-building initiatives—could be a strategic pathway to accelerate the green transition across entire industrial sectors. In this sense, firm growth can be seen not only as a consequence of successful innovation but also as a precondition for engaging more deeply with sustainability-oriented transformations. Therefore, sustainability policies should not be limited to fostering innovation per se, but should also enable structural upgrading and scaling, particularly among SMEs, which represent the backbone of most European economies yet face systemic barriers to innovation.

Membership in a conglomerate group apparently is not a determinant of innovation adoption. The *Group* variable is positive and statistically significant only in the first model (our measure of innovation adoption) for innovation in material use. This may highlight that size matters, but not for small group units. This may be because the innovation process (conceptualization, design, research, and implementation) takes place in the non-operational units of the company. These findings align with previous evidence indicating that larger firms are better positioned to leverage economies of scale and meet regulatory requirements (Horbach et al. 2012; Kesidou and Demirel 2012).

Lastly, market orientation, particularly openness to international markets, positively influences innovation adoption. In fact, nearly all innovations for the first model (i.e., adoption of innovation), apart from pollution reduction, have shown statistically significant coefficients. This highlights the relevance of external linkages and competitive exposure in triggering innovation-minded behavior, possibly due to access to broader knowledge networks and more stringent environmental standards abroad. We have not looked at whether firms produce abroad, but only at whether they export or not. Therefore, international exposure has an effect in terms of influence but not in terms of relocation outside of Italy. However, this result is not confirmed in the adoption intensity model since the *Exporter* variable is never statistically significant. This may suggest that openness to international markets may be important in terms of innovative decision-making, as Frondel et al. 2007 suggested, but it does not influence the number of innovations implemented by the firm once the adoption decision is taken.

Conversely, the location of the firm's headquarters does have an impact. Having it outside of Italy negatively impacts innovation in some domains, especially when related to energy and materials. This may be reflected in cost differentials or sector-specific characteristics. As for innovations related to energy and material use, the coefficients of this variable in the intensity adoption model showed statistically significant negative signs with a high amplitude for innovations related to materials and energy (around – 15), suggesting that firms with headquarters abroad may have a lower propensity to innovate in those specific sectors. This could be due to the industry's specificity or to the relative cost of materials and energy, which may be lower abroad than in Italy, as documented in the Draghi report (2024).

The firm's age, however, is positively associated with circular innovation adoption, suggesting that accumulated experience, established routines, and greater financial stability enhance a firm's innovation capability. Together, these findings offer a rich and nuanced understanding of how internal and external factors interact to shape innovation dynamics across different stages of the circular innovation process.

7 Conclusions

This study contributes to the literature on eco- and circular innovation by offering a comprehensive and multidimensional assessment of the drivers that influence both the adoption and intensity of circular innovation among SMEs. By employing two different models, the research disentangles the initial decision to innovate from the decision to expand the range of innovations implemented, revealing important asymmetries in the factors that influence these two stages. Our findings are relevant for modeling policies to fit the strong heterogeneity within the universe of Italian and European firms, most of which are small, resource-constrained, and more risk-averse than larger firms.

Notably, while R&D investments, human capital, and international exposure are essential for triggering innovation, their explanatory power varies once firms move beyond initial adoption. In particular, the diminishing relevance of R&D in the second model suggests that innovation maturity calls for more integrated and systemic enablers, such as organizational learning, process optimization, and network engagement. This finding underlines the importance of temporally targeted policy interventions: early-stage innovators require strong financial and cognitive support, whereas mature innovators may benefit more from ecosystem-based and collaborative frameworks.

Moreover, the study highlights the structural disadvantages faced by micro and small firms, which remain less likely to engage in circular innovation despite their centrality in the European productive fabric. This underscores the need for highly tailored policy instruments that account for the specific constraints of these firms, namely, financial, organizational, or cognitive factors. The finding that older and larger firms are more inclined to adopt and intensify eco-innovations challenges the common assumption that start-ups and young enterprises primarily drive innovation. It also suggests that a firm's accumulated capital, experience, and structural resources may be pivotal in enabling the transition toward more sustainable business models.

Although this study provides important insights, it is not without limitations. Most notably, it does not account for the level of novelty or disruptiveness of the innovations, thus overlooking potential differences between radical and incremental innovations. Future research should seek to refine this distinction, as the drivers and barriers for transformative innovations are likely to diverge from those of more incremental changes. Additionally, the economic implications of circular innovation adoption remain an open question. In addition, another limitation concerns the exclusion of regulatory drivers from our empirical analysis. Although regulation is widely recognized as a crucial determinant of eco-innovation, as mentioned in the literature section—particularly in shaping firms' incentives and compliance behavior—our dataset does not allow us to account for this dimension. As a result, the findings presented here primarily reflect the influence of internal and market-related factors. Future research should therefore explicitly integrate regulatory dynamics to provide a more comprehensive understanding of the interplay between internal, market-based, and institutional drivers of circular innovation.

Finally, while this study sheds light on what enables firms to innovate, it does not address how these innovations impact profitability, competitiveness, or long-term value creation. Addressing this gap would be crucial for assessing the strategic relevance of circularity from a firm perspective. If circular innovations can be shown to deliver tangible economic benefits, they could become not only a response to environmental imperatives but also a core component of firm-level competitive strategy, particularly for SMEs navigating an increasingly sustainability-oriented marketplace.

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