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Open eco-innovation. Aligning cooperation and external knowledge with the levels of eco-innovation radicalness

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ABSTRACT

The most pressing environmental challenges of our society require radical solutions that would redesign the ways we produce, deliver, and consume goods and services. However, little is known about what actually drives the development of radical eco-innovations. This paper explores the concept of Open Eco-innovation (OEI), an innovation model that leverages external knowledge, resources, and partnerships to enhance internal eco-innovation. Based on the sample of 2 934 Spanish firms from a mixed variety of industries, we demonstrate that an open innovation approach is crucial when firms pursue eco-innovations, particularly when aiming for more radical solutions. Unlike other studies, we show that this importance varies depending on the forms of opening (cooperation vs. sourcing external knowledge), the choice of knowledge partners, and the intended level of eco-innovation radicalness. This paper addresses a gap in understanding the selection of appropriate forms of knowledge sourcing and the choice of knowledge partners for each level of eco-innovation radicalness. Our results also point to a potential mismatch between the importance of open innovation to develop impactful and innovative environmental solutions and a small percentage of organizations adopting this innovation approach.

1. Introduction

The intensifying gravity of environmental issues demands our society to search for novel solutions and approaches to the ways we produce, deliver, and consume goods and services, as well as dispose of waste products (Westman et al., 2022; Xin et al., 2022). The changes that reduce the environmental impact of production and consumption activities are called eco-innovations (EIs) (Carrillo-Hermosilla et al., 2010). Based on the degrees of novelty and impact, such innovations are typically divided into incremental and radical (Cui et al., 2022; Kiefer, Carrillo-Hermosilla et al., 2019; Liao et al., 2020), where incremental EIs relate to minor modifications of the original products, services, and processes, and radical EIs involve considerable changes that many times disrupt the traditional business models and the ways to deliver the value to the customer (Boons and Bocken, 2018; Mothe and Nguyen-Thi, 2017). Incremental EIs currently dominate the industry and are essential in the transition of our society toward a more sustainable future (De Marchi et al., 2022; Peyravi and Jakubavičius, 2022). However, the growing consensus suggests that the rapid speed of environmental degradation and the danger of reaching the point of no return (Steffen et al., 2018) require radical and systemic, rather than incremental solutions (Boons et al., 2013; Brown et al., 2020; Dai et al., 2017).

Despite the importance, little is known about the drivers of radical EIs (Cui et al., 2022) and their possible differences from incremental EIs or other types of innovations (Kiefer, Carrillo-Hermosilla et al., 2019; Smith, 2008). But in general, academic and professional literature suggests that radical EIs tend to be more complex and usually riskier businesswise (Boons and Lüdeke-Freund, 2013; Demirel and Kesidou, 2011). As a result, organizations that strive to implement more radical changes towards sustainability face numerous barriers (Aboelmaged, 2018; Chistov et al., 2023), including the lack of knowledge and capabilities to develop EIs, redirection of limited financial resources towards non-core activities, multiple issues with capture and appropriation of the positive environmental value they provide to customers, and society in general (Ben Amara and Chen, 2020a, 2020b; González-Moreno et al., 2019; Rennings, 2000). One of the possible ways to deal with these challenges is to search for specialized knowledge,

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capabilities, and other resources outside of the firm's boundaries, through various degrees of cooperation with external partners and stakeholders (Hansen and Coenen, 2015). This process of purposeful inflows and outflows of knowledge, resources, and commercialization paths to develop or adopt eco-innovations is increasingly referred to as Open Eco-innovation (OEI) (Acebo et al., 2021; Chistov et al., 2021; Garcia et al., 2019; Ghisetti et al., 2015; Kobarg et al., 2020; Sanni and Verdolini, 2022).

The research into OEI is a rapidly developing stream in the sustainability literature (Kimpimäki et al., 2022; Pereira et al., 2020). Multiple empirical studies confirmed that R&D ties (Liao et al., 2021), close cooperation across the value chain (Levidow, Blind et al., 2016), search and adoption of external knowledge (Mothe and Nguyen-Thi, 2017; Peng and Liu, 2016), and open modes of innovation help to overcome the competence lock-in and decrease the operational risks when firms develop EIs (Chadha, 2011). OEI proved to increase the ability to comply with environmental laws and regulations (Yarahmadi and Higgins, 2012), overcome internal constraints (del Río et al., 2016), reduce financial, operational, and reputational risks (Chadha, 2011), and exploit synergies through efficient use of currently available knowledge and environmental solutions in the industry (Dijkstra, 1982). Consequently, OI showed a positive relationship with higher eco-innovation performance (Meirun et al., 2020; Mothe and Nguyen-Thi, 2016), higher environmental performance (Ben Amara and Chen, 2020a, 2020b; Rauter et al., 2019), higher economic performance (Pereira et al., 2020; Wang et al., 2019), and enhanced overall competitive advantage of the firm in the market (Klewitz et al., 2012).

A notable limitation of existing studies is the failure to distinguish among various representations of OEI (i.e., degrees of cooperation and knowledge sourcing, different forms of OEI), as well as the degrees of EI radicalness based on its novelty and impact (Brown et al., 2020). To address this research gap, we evaluate the importance of cooperation and external sources of knowledge when organizations pursue various types of EIs based on their levels of radicalness. We contribute to the research into OEI in four ways. We contribute to the research into OEI in four ways. *First,* our study enriches the existing literature by providing empirical support for the transition from the incremental-radical dichotomy of EI radicalness to more complex multi-level approaches that represent multiple degrees of radicalness (Carrillo-Hermosilla et al., 2010; Klewitz and Hansen, 2014). This shift allows for a more nuanced analysis of the relationships between different degrees of EI radicalness and their respective drivers, including the role of OEI strategies. *Second,* we bring new insights to the existing literature by illustrating the distinct effects of various open innovation strategies, such as cooperation or sourcing of external knowledge, on the environmental performance of firms, particularly in terms of EI radicalness. *Third,* we add new empirical evidence to already existing studies that emphasize the importance of inbound open innovation strategy in the form of cooperation and sourcing of external knowledge to drive the development of EI (Ghisetti et al., 2015; Kiefer, Del Río González et al., 2019; Mothe and Nguyen-Thi, 2017). However, we highlight the varying importance of these strategies based on the desired levels of EI radicalness and forms of opening. We empirically prove that cooperation and sourcing knowledge from clients and research institutions are particularly significant for more radical eco-innovations (i.e., eco-effectiveness) while also revealing the particular importance of knowledge from professional associations for incremental eco-innovations (i.e., end-of-pipe solutions) and the relevance of knowledge from suppliers for enhancing energy efficiency (i.e., eco-efficiency). These nuanced findings enrich the literature by providing a more context-specific understanding of the role of open innovation strategies in driving different types of eco-innovations, enabling organizations to better tailor their efforts to achieve desired sustainability outcomes. *Finally*, we reveal the arising OEI paradox – the mismatch between the high importance of the open innovation approach for radical EI and the low number of organizations that adopt OEI strategies.

The following section presents the theoretical background to analyze how different open innovation forms, in particular cooperation and the choice of external knowledge sources, affect the radicalness of EI. The third section explains the applied methodology and data used for empirical tests. Sections four and five summarise and discuss the findings in relation to the current literature. And the last section conveys the limitations of this study and how they might be addressed in the future.

2. Theoretical background and hypotheses

2.1. Eco-innovation and open eco-innovation

Eco-innovation (EI) can be defined as an innovation that decreases the environmental impacts of production and consumption activities (Carrillo-Hermosilla et al., 2010). Despite more than a decade of research, a precise conceptualization of eco-innovation is still missing (del Río et al., 2016; Pichlak and Szromek, 2022). The diversity in understanding eco-innovation can be attributed to the distinct aspects and characteristics that authors tend to refer to (Kiefer et al., 2017). For instance, the term eco-innovation is used both to relate to the process of developing environmental solutions as well as to solutions themselves (product or service). The changes may be of a technological nature, as well as non-technological (i.e., organizational structures and business models) (Machiba, 2010). They also may focus on consumption patterns or/and on the improvements of methods (production systems) used to create and deliver goods and services (Kulak et al., 2016). Numerous studies to date have proven its crucial role in the transition of our society towards a more sustainable future (Markard et al., 2012), as well as in simultaneously achieving the environmental and business objectives of the firm (Boons and Lüdeke-Freund, 2013). Although promising, EI is not an easy task, and many times is more complex than other types of innovations (Perl-Vorbach et al., 2014) since it is driven by potentially contradicting motivations and faces multiple challenges, including double externality and the proper ways to capture and monetize the value it provides to society (Kiefer, Del Río González et al., 2019; Rennings, 2000).

One of the possible ways to overcome these obstacles is to search for additional help, ideas, and resources outside the boundaries of the firm (Bogers et al., 2020; Perl-Vorbach et al., 2014). Cooperation and the knowledge flows from external stakeholders have been long recognized as crucial drivers of eco-innovation (del Río et al., 2016). Until recently, the research into this relationship was fragmented and dispersed among various management disciplines and multiple definitions (Chistov et al., 2021). Beginning in 2010, this research stream started to consolidate under the term Open Eco-innovation (OEI) and has experienced almost exponential growth since then (Bigliardi and Filippelli, 2022; Kimpimäki et al., 2022; Sanni and Verdolini, 2022).

Chistov et al. (2021), p. 3) define OEI as a "purposive use of inflows and outflows of knowledge, resources, and commercialization paths to develop and/or adopt innovations that improve the environmental performance of the firm." In other words, the OEI concept represents an umbrella term for activities of the company that relate to the use of external sources of knowledge and cooperation with various stakeholders to develop or adopt eco-innovations (inbound OEI) and possibly their further transfer to other organizations (outbound OEI) (Leitão et al., 2020; Naruetharadhol et al., 2021). OEI pursues two main objectives. The first is to cope with common barriers to EI, such as financial constraints, the lack of knowledge and capabilities, and incompatibility with existing business models and production processes (del Río et al., 2010; González-Moreno et al., 2019). The second is to transfer the new technologies and knowledge to other firms through the commercialization of intellectual property or in the form of positive spillovers (Pakura, 2022; Scarpellini et al., 2012). Such knowledge transfer allows firms to generate additional revenue from their R&D activities through proper patenting and their further commercialization, as well as propagate the new environmental solutions in the same (or other) industries (Chesbrough and Bogers, 2014; Curley and Salmelin, 2018). Thus, advancing and accelerating the transition of the whole society toward a more sustainable future (Bogers et al., 2020).

The research into OEI seeks to define this concept and understand the determinants of its successful adoption and implementation (Pereira et al., 2020) on various levels of analysis (Garcia et al., 2019). The micro-level explores the individual attitudes of employees and management towards the implementation of OEI and organizational characteristics that may determine its success (i.e., the size and the age of the firm, turnover, the percentage of R&D expenses, etc.) (Avellaneda-Rivera et al., 2020; Hansen and Klewitz, 2012; Pichlak and Szromek, 2021). The meso-level analyses the benefits of cooperation and transfer of knowledge for the environmental and economic performance of the firm (De Marchi, 2012), the proper ways and business models to create and capture the shared value among partners (Chang et al., 2017), the forms of cooperation, the depth and the breadth of such relationships (González-Moreno et al., 2019). The recent studies by Acebo et al. (2021) and De Marchi et al. (2022) examined how the right choice and configuration of partners affect the propensity of organizations to eco-innovate and their environmental performance. Finally, on the macro-level researchers try to understand the possible benefits of OEI on the level of industrial ecosystems (Pichlak and Szromek, 2022), national and world economy, and natural environment (Bigliardi and Filippelli, 2022; Garcia et al., 2019). For instance, recent studies indicate that OEI is crucial for the implementation and support of a circular economy (CE), a system that is designed to minimize environmental and social impacts through the conscious and continuous reuse of materials across the lifecycle of products and services (Köhler et al., 2022).

We situate our research at the meso-level and inbound OEI, investigating how an open approach to innovation (i.e., open innovation) affects the radicalness of eco-innovation in the firm. We build on multiple empirical studies that have already shown the positive relationship between open innovation and eco-innovation and expand them by recognizing that both concepts are complex and multidimensional. Therefore, we analyze the openness dimension of innovation as a combination of cooperation activities and the purposeful search and use of external sources of knowledge. We also distinguish between various types of eco-innovation according to their level of radicalness (i.e., degree of novelty and impact of eco-innovation).

2.2. Levels of radicalness in eco-innovation

The innovation literature typically distinguishes between incremental and radical types of innovation (Kiefer et al., 2021; Mendes et al., 2021; OECD and Eurostat, 2018; Triguero et al., 2018). Incremental innovations are the ones that modify the accepted processes, products, services, technologies, and business models, while radical innovations change the status quo and aim to entirely rethink and redesign the existing activities and the ways to deliver value to the customer (Adams et al., 2016). According to Dahlin and Behrens (2005), innovations can be considered radical when they are novel, unique, and have an impact on future technology. The classic economic literature suggests that radical innovations are a powerful mechanism to challenge the status quo in industries and markets, level up the ground between large and small firms, and have a dramatic impact on competition and the general survival of the firm (Schumpeter, 1934). The sustainability literature broadens this perspective and conceptualizes EI not as a dichotomy (incremental vs. radical) but rather as a spectrum (Aragón-Correa et al., 2008; Hart, 1995), distinguishing between various types of EI based on the novelty of environmental solutions and their degree of impact on society (Lin et al., 2019).

Throughout the years, various authors put forward frameworks to conceptualize various characteristics and dimensions of eco-innovation. While the terminology may differ among researchers, all frameworks contemplate that there exists a certain hierarchy between types of eco-innovation based on the extent of technological change they require and their ability to impact the status quo of doing things on a systemic level. For instance, Machiba (2010) classifies eco-innovations based on their targets (process & product, organization institutions) and mechanism (modification, re-design, alternatives, creation). Hansen et al. (2009) proposed a 3D-sustainability innovation cube that focuses on types of innovation (business model, product-service system or technological), effect (ecological, social, and economic), and the life cycle stages (manufacture, use, end-of-life). Adams et al. (2016) propose a three-dimensional framework for eco-innovations based on the innovation focus (technology or people), the level of impact (organizational changes vs. systemic changes), and the extent to which innovation extends across the firm (department level vs. firm level). We base our study on the framework proposed by Carrillo-Hermosilla et al. (2010), which analyses eco-innovation from four dimensions: design dimension, user dimension, product-service dimension, and governance dimension. This is widely accepted framework that accounted for more than 1100 citations at the beginning of the year 2023 and numerous referrals from studies on eco-innovations (Boons et al., 2013; Boons and Lüdeke-Freund, 2013; Inigo and Albareda, 2016; Klewitz and Hansen, 2014).

In particular, we focus on the design dimension of the framework, which suggests that it is possible to distinguish two different rationales for eco-innovation design. The first approach focuses on minimizing the environmental impact of human actions, whereas the second approach involves redesigning human-made systems to reduce environmental impacts. The degree of impact and the nature of technological change play a significant role in determining the appropriate approach. As illustrated in Fig. 1, by combining these factors, we can identify three distinct approaches to eco-innovation: component addition (i.e., end-of-pipe), eco-efficiency, and eco-effectiveness (see Fig. 1). These approaches can also be interpreted as the degrees of eco-innovation radicalness. It is important to mention that rather than a binary option between incremental and radical eco-innovations, framework contemplates radicalness as a scale with various levels. Accordingly, eco-innovations may be considered as less or more radical based on the levels of their impact and the novelty of implemented changes.

On the *component addition* level, organizations focus on finding additional technical components (i.e., "end-of-pipe" technologies) that minimize and repair the negative impacts of production without necessarily addressing the underlying issues that lead to environmental damage in the first place. On this level, the environmental solutions are mostly reactive and appear as a response to changes in environmental regulations and stakeholder pressure (Aragón-Correa and Sharma, 2003). While end-of-pipe eco-innovations can bring significant positive environmental impact, particularly when implemented on a large scale, it is important to recognize that they do not address the underlying causes of environmental issues. This limits their overall environmental impact and highlights the need for more systemic, transformative approaches to eco-innovation. Simply treating the symptoms of

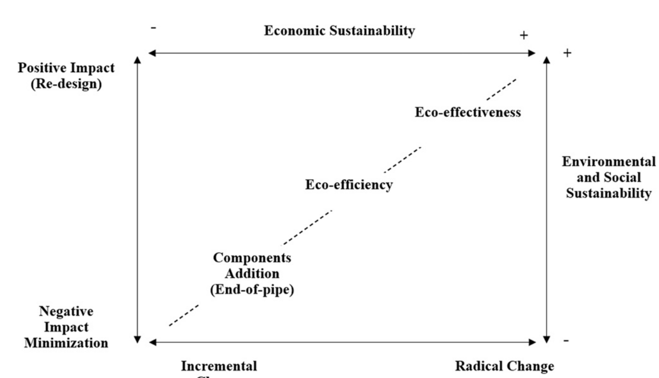

Fig. 1. Design framework for eco-innovation,
Source: Adopted from Carrillo-Hermosilla et al. (2010).

environmental problems without addressing their root causes may provide short-term benefits, but it does not lead to long-term sustainability (Triguero et al., 2015).

On the *eco-efficiency* level, organizations focus on increasing the efficiency of production, thus creating more goods and services while decreasing their environmental impact per unit of production as a result of using fewer raw materials and energy. On this level, the aim is to make the existing production systems less destructive through primarily incremental environmental solutions that reduce the firm's costs of managing end-of-pipe mechanisms, increase productivity and efficiency parameters, and parallelly decrease the firm's environmental impact (Lin et al., 2019). While eco-efficient eco-innovations can bring significant positive environmental impact, particularly when implemented on a large scale, it is important to recognize that their impact is limited by a number of factors. Such innovations focus on reducing the environmental impact of existing processes rather than fundamentally transforming them. They are often focused on improving only resource efficiency rather than addressing broader environmental and social issues (Kulak et al., 2016). This narrow focus can limit their overall environmental impact and may not adequately address the root causes of environmental problems (Levidow et al., 2016). Finally, eco-efficient innovations may also have unintended consequences, such as rebound effects, which can offset their positive environmental impact over time (Chenavaz et al., 2021). As such, on the systemic level, their impact is more incremental rather than radical.

Finally, on the level of *eco-effectiveness*, firms seek to completely rethink and redesign the existing ways to produce and deliver products or services and make them biocompatible (compatible with other Earth systems) while still creating commercial added value for customers (Carrillo-Hermosilla et al., 2009; del Río et al., 2021). Such radical changes allow for addressing the root causes of environmental problems rather than simply treating the symptoms (Schaefer et al., 2015). They bring changes to technological systems that are sustainable over the long term rather than providing short-term solutions that may have unintended consequences. By rethinking entire systems, including production processes, supply chains, and consumer behavior, eco-effective systemic eco-innovations can create a more holistic approach to environmental sustainability that addresses social, economic, and environmental issues together (Russo Spena and Di Paola, 2020). While such innovations may require more resources and time to implement, their impact can be far-reaching and transformative, creating lasting benefits for both people and the planet.

In general, EIs are expected to be more radical than other types of innovation because, in most cases, they do not form part of the firm's core activities (Horbach et al., 2013) and may be novel to the organization, as well as to the market and industry (del Río et al., 2015; Kiefer et al., 2019). Such innovations tend to be more complex, require more specialized resources and capabilities, and many times are riskier businesswise (Boons and Lüdeke-Freund, 2013; Demirel and Kesidou, 2011). They also face the issue of double externality, when firms struggle to appropriate the value they provide to society due to involuntary knowledge spillovers and consideration of the Environment as a public good (Gonzalez, 2004; Rennings, 2000). Due to the severity of environmental challenges, the prevailing consensus among scientists and political elites is that end-of-pipe and eco-efficiency solutions are not enough, and our society needs to rethink the current ways of production, delivery, and consumption of products and services completely (Lin et al., 2019; Steffen et al., 2018). As a result, organizations face the double challenge of introducing EIs and ensuring their high degrees of novelty and positive environmental impact.

Despite the increasing interest in the academic literature (Mutira et al., 2022), it is still not clear what drives EIs to be less or more radical (Cui et al., 2022). The available empirical evidence suggests that they appear as a consequence of regulatory and green market pressure, availability of knowledge, resources, and capabilities (Chadha, 2011; Levidow, Blind et al., 2016), environmentally and innovation-oriented business cultures (Kiefer et al., 2019). Also, such innovations tend to extend beyond the boundaries of one firm and commonly require the understanding and involvement of various stakeholders to achieve higher levels of change (Hansen and Coenen, 2015). According to OI literature, the interaction with external partners represents the flow of knowledge and resources between organizations that can be intentionally managed through various forms of cooperation and intellectual property (Chesbrough, 2003a, 2003b). In this vein, in this study, we aim to investigate how cooperation and knowledge flow from various external partners, such as suppliers, clients, competitors, universities, research centers, consultants, and other intermediaries, contribute to various levels of the radicalness of EI.

2.3. Cooperation and radicalness of eco-innovation

The flow of knowledge across the boundaries of the firm may take various forms, i.e., acquisition from other firms through outsourcing, licensing, and consulting; crowdsourcing challenges and competitions; corporate startup incubators and accelerators, mergers, and acquisitions, partnerships with various external stakeholders (Wu, 2022). All of them require some degree of interaction between two or more organizations (Chesbrough, 2003a, 2003b). One of the highest degrees of interaction is cooperation when partners actively participate in joint research and development (R&D) projects (Ryszko, 2016; Tether, 2002).

The literature on EI considers cooperation as one of the antecedents and a crucial driver of EI (Mazzanti and Zoboli, 2009; Rennings and Rammer, 2011), as well as an essential element of OEI strategy (Zhang et al., 2022). Various literature and bibliometric reviews showed that researchers started to analyze this relationship around three decades ago, and the interest only grows over time (Araújo and Franco, 2021; Melander, 2017; Pereira et al., 2020). The early studies suggested that close cooperation with governmental organizations may help to ensure compliance with environmental laws and regulations and minimize the risk of severe financial penalties (Oliver, 1991). And that cooperation with a broad public and interest groups increases the legitimacy (public acceptance) and credibility of firms (Bansal and Roth, 2000). Moreover, close interaction with stakeholders helps to understand better their sustainability concerns and avoid potential conflicts of interest in the future (Gold et al., 2009). The latter research showed that EI is associated with higher levels of uncertainty, complexity, and novelty than general innovations (Horbach et al., 2013; Triguero et al., 2013). In this context, close partnerships with external organizations may help to deal with the lack of in-house knowledge, resources, and capabilities to develop novel environmental solutions (De Marchi, 2012; Horbach, 2008; Petruzzelli et al., 2011), as well as to share the innovation and commercial risks (Aboelmaged, 2018). Cooperation may also lead to synergies among partners, which would allow to cut costs of EI R&D (Souto and Rodriguez, 2015), to take advantage of economies of scale (Fabrizi et al., 2018), increase the efficiency and effectiveness of processes (Sánchez-Sellero and Bataineh, 2021), and decrease the time to introduce new green products and services to the market (Melander, 2018; Peñasco et al., 2017).

In summary, cooperation helps organizations to comply with environmental regulations, increase their legitimacy, decrease financial and reputational risks, supplement the internal R&D process with external knowledge and resources, increase efficiencies, and understand their customers better, which all leads to higher competitive advantages in the market (Ghisetti et al., 2015; Triguero et al., 2013). Overall, different forms of cooperation showed a direct positive effect (Calza et al., 2021) or positive moderation and mediation effects on the environmental performance of firms (Martinez-Sanchez et al., 2009). Multiple empirical studies proved that it is indeed an essential driver of eco-innovation (Arranz et al., 2019; De Marchi, 2012; Horbach, 2016). In fact, the research even suggests that EI is particularly dependent on cooperation and external sources of knowledge, in contrast to general innovation (De Marchi, 2012; Higgins and Yarahmadi, 2014; Horbach, 2008).

Much less is known about the role of cooperation on different levels of EI radicalness. Studies show that radical and systemic types of EIs are more complex than incremental EIs and have higher requirements in terms of funding and internal innovation capabilities (Kiefer et al., 2018). They also often require changes in the supply chain and business models, thus making cooperation with various stakeholders inevitable (Cainelli et al., 2015; De Marchi, 2012; Kanda et al., 2018). According to Brown et al. (2020), incremental EI allows organizations to start small and develop the necessary capabilities, but radical EI will require more complex and costly collaborations to move toward new systems of production and consumption. Cooperation and OI strategies showed the potential to strengthen the propensity of the firm to generate radical EI (Pichlak and Szromek, 2021). The prior research also revealed that cooperation is equally important for radical EIs in small firms that are usually constrained in resources (Halme and Korpela, 2014; Wagner and Llerena, 2011), as well as large firms that require public-private partnerships, legitimacy, and appropriate regulations to diffuse large-scale environmental technology systems (Kanda et al., 2016).

In summary, we can conclude that while cooperation brings additional levels of complexity and there exist a certain hesitance to partner up to develop EIs, it affects positively incremental EIs, and is especially important for radical EIs (Inigo et al., 2020; Mothe and Nguyen-Thi, 2016). Accordingly, in this study, we hypothesize that cooperation will exhibit a positive relationship at each level of EI radicalness (i.e., components addition, eco-efficiency, and eco-effectiveness) and will be especially important at the eco-effectiveness level. Therefore, we formulate the following hypotheses:

H1. . *Cooperation is positively related to eco-innovation at all levels of radicalness - (a) Component Addition; (b) Eco-efficiency; (c) Eco-effectiveness.*

H2. . *Cooperation is particularly important for higher levels of eco-innovation radicalness (*i.e.*, eco-effectiveness level).*

2.4. External knowledge sources and radicalness of eco-innovation

The original research into OEI treated cooperation as an independent self-containing variable and tried to understand the general effect of collaboration on the environmental and business performance of the firm (Kennedy et al., 2017). However, recent advancements show that it is a complex phenomenon that depends on a broad array of specific determinants (Chistov et al., 2021; Garcia et al., 2019). OEI literature suggests that behind cooperation, there is a flow of knowledge and resources between two or more organizations that should support their individual or mutual business objectives (Chesbrough, 2003a, 2003b). According to the knowledge-based view, knowledge is one of the crucial resources for any organization and should be properly managed (Grant, 1996). Therefore, companies have to develop critical capabilities to search and acquire complementary knowledge outside of their boundaries (i.e., knowledge scouting), delineate the proper knowledge sources, establish proper ways and protocols to transfer the knowledge (i.e., knowledge sharing), and properly integrate it into the existing organizational processes (i.e., absorptive capacity) (Albort-Morant et al., 2018; Song et al., 2021).

One of the rising topics in the OEI literature is the matter of proper selection of knowledge sources (De Marchi et al., 2022, p. 202; Kobarg et al., 2020; Santos et al., 2021; Solesvik, 2018). The classic innovation literature posits that the production of new ideas stems from a function that reconfigures old ideas, creating a combinatoric feedback process where knowledge builds upon itself, potentially impacting economic growth (Weitzman, 1998). Studies show that radical innovations rely heavily on a firm's ability to consolidate an abundance of potential new ideas into a stable form of a product or service; however, the open innovation approach recognizes that the best knowledge and ideas are not confined within a single firm's boundaries (H. Chesbrough and Bogers, 2014). Consequently, organizations are forced to match their internal skills with distinctive, complementary, and sometimes unique competencies of external organizations (Ben Arfi et al., 2018; Caloghirou et al., 2004).

However, tapping into external sources of knowledge and choosing the right knowledge partner is not an easy task. *First*, case studies show that, in practice, partners and their attitudes have the power to "make or break" all the collaboration efforts of the firm (Pujari et al., 2003; Rizzi et al., 2013). *Second*, from a management perspective, the search for external knowledge and collaboration with stakeholders may entail the reallocation of internal personnel, time, and resources from the core activities of the firm, thus jeopardizing its business performance (Horbach et al., 2013; Klewitz and Hansen, 2014; Petruzzelli et al., 2011). *Third*, managers often have to make decisions under conditions of uncertainty since they rarely have full information about their partners and struggle to predict the real positive affect of a combination of knowledge and expertise among firms (Fleming, 2001; Rosenberg, 1996; Solesvik, 2018). *Fourth*, according to innovation search theory, there exists a point when the amount and complexity of external knowledge become too hard to handle, and organizations may start making mistakes (Koput, 1997; Stucki and Woerter, 2022). Also, an excessively broad network of external partners and sources of knowledge brings additional complexity to the open innovation structures that can have more negative effects on eco-innovation than positive (Hermann et al., 2016). *Finally*, recent empirical research suggests that specific sustainability objectives of the firm may require knowledge from specific partners or a combination of partners. And that the mismatch between them may lead to lower efficiency and effectiveness of OEI endeavors (De Marchi et al., 2022; Kobarg et al., 2020). In summary, the choice of external knowledge sources, their combination, the depth, and the breadth of collaboration are of strategic importance and has to be tailored to the particular needs and goals of the firm (Acebo et al., 2021; Sanchez-Henriquez and Pavez, 2021).

The existing research explores various possible approaches and dimensions to understand the selection process of knowledge sources and partners for OEI. Several studies reviewed the potential optimal number of external knowledge sources and partners in the network (the breadth of collaboration) and how close this partnership should be (the depth of collaboration) (Ghisetti et al., 2015; Juntunen et al., 2019). Some studies explore the advantages and disadvantages of collaboration with a specific type of partner in isolation, including suppliers (Melander and Pazirandeh, 2019; Potter and Graham, 2019), universities (Song et al., 2020), and competitors (Li et al., 2021), or the impact of a particular group of partners, such as value chain partners (suppliers and customers) (Ocicka et al., 2022), or intermediaries (government agencies, consultants, public universities and research centers) (Al-Hanakta et al., 2021; Kanda et al., 2020). Other studies are able to leverage the available data and compare the impacts among the partners on environmental performance in the same context and using the same data (Kobarg et al., 2020; Sanchez-Henriquez and Pavez, 2021). Finally, while the conventional perspective on the matter suggested that due to the systemic nature of EI, it requires knowledge from a broad array of partners and stakeholders that is complimentary (Horbach et al., 2012) (suggesting that all the partners may be equally significant), Acebo et al. (2021) and De Marchi et al. (2022) found that the knowledge from various sources should also be compatible and that the combination of specific knowledge partners in the open innovation network also matters and may lead to positive or negative effects on environmental and business performance of the firm, being particularly relevant for more radical eco-innovations (Shou et al., 2018).

The OEI literature, however, does not yet provide clear guidance for the selection of knowledge sources according to the levels of EI radicalness. The scarce empirical evidence suggests that due to considerable business risks, difficulty to manage, and inherent uncertainties, radical

EIs may require cooperation with public clients that could share the burden of innovation risks, establish favorable conditions, provide a first-hand perspective on governmental environmental strategies and regulations, and connect the firm with other stakeholders (Lenderink et al., 2022). Close cooperation and sourcing knowledge from suppliers draw important attention in OEI literature (Chistov et al., 2021), but their association with radical EIs is controversial. While some studies show a positive relationship with both incremental and radical EIs (Roscoe et al., 2016; Zhang et al., 2020), others point out that the overestimated trust in suppliers can have a negative impact on radical EIs (Zhao et al., 2020). Additionally, universities and research centers are also considered as crucial knowledge partners and allow organizations to upgrade internal technological capabilities as well as decrease the inherent risks of eco-innovation (Scarpellini et al., 2017). These sources of knowledge are especially beneficial for eco-product innovation (Triguero et al., 2013) and essential for radical EIs (del Río et al., 2015).

We extend this line of research and explore the importance of sources of external knowledge on various levels of EI radicalness based on their novelty and impact. In line with the previous research, we anticipate a generally positive relationship. However, we also expect that the importance of particular sources of knowledge may not be consistent throughout all the levels of EI radicalness. Thus, we pose our next hypotheses:

H3. *External knowledge sources are positively related to the different levels of eco-innovation radicalness– (a) End-of-pipe, (b) Eco-efficiency, (c) Eco-effectiveness.*

H4. *The importance of the different external knowledge sources varies according to the level of the radicalness of eco-innovation.*

3. Methodology

3.1. Sample

In order to test our hypotheses, we use the data from the Spanish Technological Innovation Panel (PITEC), a survey prepared and distributed by the National Institute of Statistics in Spain (INE) and the Spanish Foundation for Science and Technology (FECYT). It has a goal of evaluating technological activities in Spanish companies. The database started to collect information in 2003 and offers more than 460 variables based on answers from more than 12,000 companies distributed among different sectors and locations in Spain. PITEC is closely based on the Community Innovation Survey (CIS) – a survey on the innovativeness of sectors that provides information about firms' characteristics, the types of innovation they pursue, and various aspects of their R&D development. This survey is one of the most used sources of empirical data in the literature on EI and open innovation (De Marchi, 2012; del Río et al., 2016; Ghisetti et al., 2015; Horbach et al., 2012). The limitation of this database is that the companies access and report their innovation activities independently and that the results may be subjective (Saez-Martinez et al., 2016).

The PITEC data set is an unbalanced panel and offers the possibility to track the same sample of organizations at different points in time. There exist several approaches to choosing the period for investigation. First, to analyze the data from several consecutive years, which is particularly useful when authors introduce the lagged explanatory variables (Acebo et al., 2021; Hernández-Trasobares and Murillo-Luna, 2020). The second is to choose only one year for observation since the changing nature of the sample and questionnaire in PITEC may pose challenges for inter-temporal analyses. In this study, logistic regression is employed as the primary statistical model due to the nature of the dependent variables. However, using this method with unbalanced panel data can introduce various challenges, such as biased estimates, efficiency loss, model misspecification, and difficulties managing missing data. Consequently, we chose to analyze variables from a single observation period for our primary models. We utilized the 2016 data, which is the latest available survey published by the National Statistics Institute of Spain. The original 2015–2016 dataset contained observations for 12,849 firms. We excluded firms that experienced sudden changes in employment due to mergers, acquisitions, or high labor turnover (Acebo et al., 2021; González-Pernía et al., 2015) and firms that did not report on their eco-innovation activities. The resulting sample is composed of 2934 firms.

3.2. Measurement of Variables

3.2.1. Dependent variables

The main dependent variables of this research represent the objectives of the firm to reach a particular level of eco-innovation radicalness. PITEC survey follows the Oslo Manual guidelines and defines innovation as "a new or improved product, or process (or a combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)" (OECD and Eurostat, 2018, p.20). As a proxy to the *component's addition* level, we use the variable that shows if the objective of innovation was to comply with the environmental regulations since they traditionally favor the end-of-pipe solutions and impose minimal standards, that balance between the environmental impact of the firm and its profitability (Frondel et al., 2007). To analyze the level of *eco-efficiency*, we originally created a new variable that combined innovation goals that focused on the decrease in material and energy use per unit of production. However, later we also tested models where those two goals were separate. We concluded that while conceptually they represent the general efficiency of the production process, in practice, they tend to require different sets of expertise and different combination of knowledge sources. As a result, we left both of them separated in the model. Finally, we have created a new variable to represent the level of *eco-effectiveness* that combines two variables (i.e., the interaction between these two variables): the variable measuring that the firm has "innovation goals that focus on decreasing the general environmental impact of the firm" and the variable regarding the innovation goals "to develop technologies that are new to the market." All the dependent variables are dichotomic, and most of them (except the variable on eco-effectiveness) take the value (1) if the innovation objective has high relevance for the firm, and zero (0), if it is of low relevance. In the case of eco-effectiveness, the variable takes the value one (1) if the decrease of the environmental impact was an innovation priority of the firm and if it used technologies that were not currently available in the market, and it took the value of zero (0) if the objective to decrease the environmental impact was of low importance or the technology used was not new to the market. In the context of our research, value (1) indicates the intention of the firm to pursue a particular level of EI radicalness.

3.2.2. Independent variables

The explanatory variables in our study represent cooperation and the importance of various sources of external knowledge for organizations during the innovation process. This is an example of inbound open innovation when the knowledge is sourced outside the boundaries of an organization (Chesbrough and Bogers, 2014). The database provides information on the relevance of particular stakeholders as sources of external knowledge. The variables are dichotomic. The cooperation variable takes the value (1) if the organization actively cooperated with external partners during the innovation process and (0) if an organization didn't cooperate with external partners. Variables for external knowledge sources take the value one (1) if a particular knowledge source was considered relevant and zero (0) in cases where a particular external knowledge source was irrelevant. This set of variables includes sourcing knowledge from suppliers, clients, competitors, consultants, universities, research centers (with the distinction between public and private), and professional associations.

3.2.3. Control variables

In order to control for factors that also might have an impact on the radicalness of eco-innovation, we included a set of variables that previously proved to have such an impact, considering: the *Age* of the firm that shows its general experience in the market; *Size* of the firm: *Small* (less than 50 employees), *Medium-sized* (51–250 employees), and *Large* (more than 250 employees). Moreover, *Export*-orientation of the firm, since the international regulations tend to inspire firms to strive for higher levels of eco-innovation (González-Pernía & Peña-Legazkue, 2015; Triguero et al., 2018). We also included a list of sectors that were previously explored in the literature, such as the agriculture sector (Silvestri et al., 2022), food sector (Triguero et al., 2018), hospitality sector (Aboelmaged, 2018), and manufacturing sector (Acebo et al., 2021).

3.3. Statistical Method

To test our hypotheses, we use binomial logistic regression. We chose this method based on several reasons. First, is due to the dichotomous nature of our variables. Second, while our data allows constructing the dependent variable of EI radicalness as a scale variable, we did not opt for this option since that would indicate the hierarchical relationship between the three levels of radicalness. In reality, organizations may simultaneously pursue various degrees of EI radicalness (i.e., *components addition, eco-efficiency* and *eco-effectiveness*). We also wanted to compare and draw conclusions from comparing the levels among each other. Our models and the statistical method allowed us to take into consideration these concerns.

In contrast to the ordinary least squares regression, logistic regression estimates a probability of a particular event to happen. In our study, this event is reaching various levels of eco-innovation radicalness. We can represent the relationship between the binary dependent variable (levels of eco-innovation radicalness) with multiple independent variables (i.e., cooperation, various sources of knowledge) with the following formula: $\text{Log(odds)} = \text{Log}(p / (1 - p)) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$, where log(odds) is the natural logarithm of the likelihood of a firm to pursue one of the levels of eco-innovation radicalness (value one (1)) and zero (0) otherwise (Greene, 2003; Hosmer and Lemeshow, 2004). Here p is the probability of the dependent variable being equal to 1 given the values of the independent variables x_1, x_2, x_3, and x_4, β_0 (beta zero) is the intercept, which represents the log (odds) when all independent variables are equal to 0, and β_1, β_2, β_3, and βn are the coefficients for the independent variables x_1, x_2, x_3, and x_n, respectively, which represent the change in log(odds) for a one-unit increase in each independent variable, holding all other independent variables constant (i.e., cooperation; sources of external knowledge) and control variables (i.e., age, size, export orientation).

In this study, we employed Nagelkerke's R-square as a measure to assess the goodness of fit for our logistic regression model. It is crucial to note that Nagelkerke's R-square, also known as pseudo-R-squared, represents the proportional reduction in the absolute value of the log-likelihood measure, rather than the amount of variance accounted for, as in linear regression analysis. It ranges from 0 to 1, with values closer to 1 indicating a better fit of the model. We use the SPSS statistical package to test our models.

3.3.1. Robustness check

To evaluate the structural validity of the proposed models, we perform the robustness test. The model is considered robust when the “core” regression coefficient estimates behave similarly when the regression parameters are modified by adding or removing regressors (Lu and White, 2014). In this study, we first perform the sensitivity test by removing control variables, thus eliminating their possible influence on the models. Another way of testing robustness is by switching dependent and independent variables with very similar substitutes. The characteristics of our data allow us to use the lagged variables for cooperation and external sources of knowledge from the 2015 version of the PITEC survey. The use of lagged explanatory variables is one of the common ways to address the issue of delays between the introduction of new organizational practices and their impact (González-Pernía et al., 2015). Consequently, in our robustness models, the dependent variables are from 2016, and the independent variables are from 2015 (the lagged variables), and we do not include the control variables. We expect that the importance of cooperation and external sources of knowledge for the firm does not dramatically change in a matter of one year (from 2015 to 2016) and that they will excerpt a similar relationship with different levels of EI radicalness.

4. Results

4.1. Multicollinearity and quality of the models

First, we examined the quality of our main models and the variables that were included in the models. The variance inflation factors (VIF) of all the variables fell within an acceptable range (i.e., under 5.0), therefore, we discarded the possible issues related to multicollinearity (see Table 2). The omnibus test for all our models (both main and robustness models) showed an acceptable significance of 0.00 (less than 0.05), indicating that they outperformed the null models. Furthermore, we evaluated their "goodness of fit" based on Nagelkerke's pseudo-R2. Unlike the ordinary least square-R2, it does not represent a proportion of explained variance, but the improvement in the likelihood of the model over the null model and can be compared to other pseudo-R2 derived from the same data, using the same set of explanatory variables, or predicting the same outcome (Hemmert et al., 2018). In the case of our main models (see Table 3), the model for eco-effectiveness showed the best results (18%), followed by component addition (17.9%), energy efficiency (16.3%), and material efficiency (15.7%).

4.2. Descriptive analyses

Descriptive analyses carried out included a frequency analysis and a correlation analysis (Table 1 and Table 2). The frequency analysis showed a quite balanced representation of small (37.9%), medium (37.1%), and large (25.1%) firms in our sample made by 2 934 observations. We noticed a significant positive correlation between the small firms and eco-innovations that focus on compliance and eco-efficiency (i.e., less radical eco-innovations) and a negative significant

Table 1
Descriptive Analysis I: Frequency Analysis.

	Frequency	Valid Percent
Component Addition	1653	56.3%
Material Efficiency	1271	43.3%
Energy Efficiency	1324	45.1%
Eco-effectiveness	973	33.2%
Cooperation	1528	52.1%
Small firms	1111	37.9%
Medium-sized firms	1088	37.1%
Large firms	735	25.1%
Firm Market: National	2793	95.2%
Firm Market: International	2116	72.1%
Belonging to a group of companies	1604	54.7%
Introduction of products that are new to the firm	2294	78.2%
Introduction of products that are new to the market	1607	54.8%
Agriculture Sector	18	0.6%
Food Sector	241	8.2%
Hospitality Sector	12	0.4%
Manufacturing Sector	844	28.8%
Total number of respondents	**2934**	**100%**

Source: Authors’ elaboration.

Table 2
Descriptive Analysis II: Descriptive Statistics and Correlation Matrix.

	Mean	VIF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Component Addition	2.4	1.699																					
Material Efficiency	2.71	2.741	0.494 * *																				
Energy Efficiency	2.67	3.001	0.556 * *	0.789 * *																			
Eco-effectiveness	0.33	1.368	-0.452 * *	-0.304 * *	-0.351 * *																		
Cooperation	0.52	1.222	-0.176 * *	-0.126 * *	-0.157 * *	0.232 * *																	
Suppliers	0.66	1.209	-0.220 * *	-0.228 * *	-0.241 * *	0.126 * *	0.139 * *																
Private Clients	0.65	1.469	-0.236 * *	-0.220 * *	-0.212 * *	0.187 * *	0.156 * *	0.263 * *															
Public Clients	0.34	1.379	-0.155 * *	-0.140 * *	-0.135 * *	0.141 * *	0.143 * *	0.176 * *	0.439 * *														
Competitors	0.48	1.308	-0.187 * *	-0.192 * *	-0.168 * *	0.108 * *	0.140 * *	0.258 * *	0.356 * *	0.312 * *													
Consultants	0.35	1.420	-0.209 * *	-0.182 * *	-0.193 * *	0.181 * *	0.240 * *	0.257 * *	0.220 * *	0.266 * *	0.328 * *												
Universities	0.33	1.853	-0.188 * *	-0.171 * *	-0.204 * *	0.233 * *	0.322 * *	0.136 * *	0.180 * *	0.258 * *	0.203 * *	0.369 * *											
Public Research Centers	0.28	2.217	-0.203 * *	-0.176 * *	-0.203 * *	0.262 * *	0.313 * *	0.166 * *	0.205 * *	0.271 * *	0.219 * *	0.381 * *	0.630 * *										
Private Research Centers	0.32	2.007	-0.226 * *	-0.201 * *	-0.232 * *	0.261 * *	0.330 * *	0.195 * *	0.238 * *	0.251 * *	0.228 * *	0.411 * *	0.548 * *	0.657 * *									
Professional Associations	0.35	1.305	-0.231 * *	-0.181 * *	-0.207 * *	0.179 * *	0.180 * *	0.226 * *	0.243 * *	0.287 * *	0.270 * *	0.329 * *	0.312 * *	0.323 * *	0.318 * *								
Age	40.75	1.107	-0.086 * *	-0.061 * *	-0.074 * *	0.043 *	0.047 *	0.040 *	-0.019	-0.025	0.009	0.041 *	-0.013	-0.001	0.010	0.018							
Small firm	0.38	1.353	0.118 * *	0.118 * *	0.120 * *	-0.102 * *	-0.143 * *	-0.124 * *	0.007	-0.035	-0.064 * *	-0.103 * *	-0.083 * *	-0.097 * *	-0.096 * *	-0.065 * *	-0.253 * *						
Large Firms	0.25	1.368	-0.062 * *	-0.069 * *	-0.075 * *	0.102 * *	0.139 * *	0.078 * *	-0.036 *	0.051 * *	0.037 *	0.110 * *	0.082 * *	0.073 * *	0.064 * *	0.053 * *	0.228 * *	-0.451 * *					
Export Orientation	0.72	1.161	-0.132 * *	-0.147 * *	-0.119 * *	0.094 * *	0.027	0.018	0.177 * *	0.028	0.060 * *	0.041 *	0.058 * *	0.063 * *	0.084 * *	0.007	0.079 * *	-0.071 * *	-0.114 * *				
Agriculture Sector	0.01	1.016	0.021	0.021	0.027	-0.009	0.005	-0.045 *	-0.006	-0.001	0.003	0.024	0.056 * *	0.067 * *	0.058 * *	0.025	-0.021	0.011	-0.025	-0.039 *			
Food Sector	0.08	1.076	-0.058 * *	-0.035	-0.060 * *	-0.021	-0.006	0.023	0.011	-0.029	0.012	0.041 *	0.015	0.041 *	0.041 *	0.025	0.045 *	-0.103 * *	0.073 * *	0.039 *	-0.024		
Hospitality Sector	0.00	1.024	0.036	0.017	0.029	-0.034	-0.003	-0.010	-0.031	-0.023	-0.008	0.008	-0.033	-0.017	-0.033	-0.002	0.007	-0.050 * *	0.099 * *	-0.103 * *	-0.005	-0.019	
Manufacturing Sector	0.29	1.186	-0.080 * *	-0.133 * *	-0.106 * *	0.023	-0.066 * *	0.031	0.095 * *	-0.029	0.003	-0.066 * *	-0.104 * *	-0.076 * *	-0.041 *	-0.094 * *	0.038 *	0.016	-0.138 * *	0.242 * *	-0.050 * *	-0.190 * *	-0.041 *

N = 2 934 observations
*p < 0.01; * *p < 0.05; * **p = 0.00
Source: Authors' elaboration.

Table 3
Main Models.

		Component Addtition (Exp (β))	Eco-efficiency (Exp (β))		Eco-effectiveness (Exp (β)))
			Materials	Energy	
Knowledge Sources	Cooperation	1.309 **	1.059	1.231 **	1.803 ***
	Suppliers	1.473 ***	1.662 ***	1.788 ***	1.161
	Private Clients	1.443 ***	1.351 **	1.241 **	1.706 ***
	Public Clients	1.179 *	1.100	1.003	0.990
	Competitors	1.189 *	1.326 **	1.205 **	0.889
	Consultants	1.143	1.196 *	1.112	1.104
	Universities	1.214 *	1.183	1.337 **	1.224 *
	Public Research Centers	1.192	1.116	1.046	1.536 **
	Private Research Centers	1.250 *	1.201	1.352 **	1.414 **
	Professional Associations	1.610 ***	1.424 ***	1.534 ***	1.325 **
Control Variables	Age	1.004 **	1.000	1.002	1.001
	Small firms	0.815 **	0.800 **	0.860	0.869
	Large Firms	1.063	1.237 **	1.208 *	1.443 **
	Export Orientation	1.421 ***	1.348 **	1.297 **	1.369 **
	Agriculture Sector	0.820	1.015	0.863	0.606
	Food Sector	1.700 **	1.274	1.562 **	0.701 **
	Hospitality Sector	0.374	0.607	0.317	0.192
	Manufacturing Sector	1.593 ***	1.883 ***	1.666 ***	1.164
	Constant	0.244 ***	0.171 ***	0.168 ***	0.105 ***
	R2	17.9%***	15.7%***	16.3%***	18%***
	N	2934	2934	2934	2934

N = 2 934 observations
*p < 0.01; **p < 0.05; ***p = 0.00
Source: Authors' elaboration.

correlation with more radical eco-innovations. Interestingly, the large firms demonstrated a completely reverse dynamic. These results are in line with previous studies that showed that due to liabilities of newness and smallness (Wagner and Llerena, 2011), and the lack of resources, radical EIs might be out of reach for small firms (Lacy and Rutqvist, 2015), and they engage only in lower levels of EI radicalness (i.e., components addition and eco-efficiency) (Kiefer et al., 2021).

Regarding age, the mean age in the sample was 41 years old. Less than 0.02% of organizations were younger than ten years old. Thus, the results of our investigation represent the dynamics in mature firms rather than new ventures. Moreover, we observe a negative correlation between age and lower-impact environmental objectives and a positive significant correlation with higher-impact environmental objectives. In summary, more radical EIs were positively associated with larger and older firms. In contrast, the less radical types of eco-innovations (i.e., those including objectives of environmental compliance and eco-efficiency) were positively associated with younger and smaller firms. The existing literature does not provide a definitive perspective on the influence of a firm's age on radical EI, however, there exist some indications that due to high complexity, it requires an accumulation of internal innovation capacity that normally happens with time (del Río et al., 2015).

As far as the industry is concerned, we find that manufacturing firms constituted 28.8% of our sample, and the rest of it was distributed among other industries, including agriculture, food production, pharmaceuticals, energy production and networks, hospitality, IT, and others. 54.7% of firms belong to a group of companies, and 7.3% of them are located in industrial parks.

With regard to export orientation, more than 95% of companies focus on local and national markets, but there is also a considerable number (72.1%) that target international markets. We found that the export orientation of firms was positively correlated with more radical eco-innovations and negatively correlated with less radical eco-innovations (i.e., firms pursue other environmental objectives, such as compliance and efficiency). These results coincide with the analysis performed by Torrecillas and Fernández (2022), which also used the PITEC data.

On the other hand, we found that there exists a difference in the percentage of firms according to the radicalness of eco-innovation. While more than half of the firms strive to comply with environmental regulations (56.3%) (i.e., end-of-pipe solutions), less than half of them innovate to increase their material (43.3%) and energy efficiency (45.1%) (i.e., eco-efficiency level), and only 33.2% pursue more radical EI (i.e., eco-effectiveness; new-to-the-market). This is also consistent with previous studies that suggest that incremental environmental solutions are easier to implement than more radical ones (Carrillo-Hermosilla et al., 2009) Finally, only half of the firms in the sample (52.1%) reported active cooperation with external partners during the eco-innovation process, and much less whenever they pursued more radical eco-innovation objectives: compliance/end-of-pipe (33%), material efficiency (25%), energy efficiency (27%) and eco-effectiveness (i.e., radical eco-innovation) (23%).

4.3. Main models analysis

Table 3 presents the results of the analysis of the main models and hypotheses testing, in particular, the impact of cooperation and various external knowledge sources on different types of eco-innovation (i.e., different levels of eco-innovation radicalness). Our results show (see Table 3) that firms that cooperated with external partners during the innovation process were 31% more likely to pursue the goal of compliance with environmental regulations (i.e., components addition) (i.e., *Exp (β)* = 1.309, $p < 0.01$), 23% more likely to focus on energy efficiency (i.e., *Exp (β)* = 1.231, $p < 0.01$), and 80% more likely to pursue more radical eco-innovations (i.e., *Exp (β)* = 1.803, $p = 0.00$). We did not get any significant results for the case of material efficiency.

Regarding the external sources of knowledge, firms that consider the information from suppliers important are 47% more likely to be pursuing the goal of compliance with environmental regulations (i.e., *Exp (β)* = 1.473, $p = 0.00$), 66% - material efficiency (i.e., *Exp (β)* = 1.662, $p = 0.00$), and 79% - energy efficiency (i.e., *Exp (β)* = 1.788, $p = 0.00$). However, we did not get any significant results for the eco-effectiveness level. Companies that reported the high importance of knowledge from private clients were 44% more likely to focus on compliance with regulations (i.e., *Exp (β)* = 1.443, $p = 0.00$), 35% on material efficiency (i.e., *Exp (β)* = 1.351, $p < 0.01$), 24% on energy efficiency (i.e., *Exp (β)* = 1.241, $p < 0.01$), and 71% on more radical eco-innovations (i.e., *Exp (β)* = 1.706, $p < 0.01$). Both public (i.e.,

Table 4
Robustness and Sensitivity Test.

		Component Addtition *(Exp(β))*	Eco-efficiency (Exp (β))		Eco-effectiveness *(Exp(β))*
			Materials	Energy	
Knowledge Sources	Cooperation	1.594 ***	1.219 **	1.414 ***	2.186 ***
	Suppliers	1.467 ***	1.660 ***	1.731 ***	1.202 *
	Private Clients	1.506 ***	1.312 **	1.231 **	1.439 **
	Public Clients	0.956	1.319 **	1.150	0.871
	Competitors	1.095	1.142	1.157	1.056
	Consultants	1.221 *	1.172	1.109	1.179
	Universities	1.107	0.816	0.879	1.091
	Public Research Centers	1.115	1.507 ***	1.600 ***	1.426 **
	Private Research Centers	1.486 ***	1.065	1.110	1.493 ***
	Professional Associations	-	-	-	-
	R2	10.1%***	8.3%***	9.3%***	12.5%***
	N	2934	2934	2934	2934

N = 2 934 observations
*p < 0.01; * *p < 0.05; * **p = 0.00
Source: Authors' elaboration.

Table 5
Relationship of cooperation and external sources of knowledge with levels of eco-innovation radicalness.

		Component Addtition	Eco-efficiency		Eco-effectiveness
			Materials	Energy	
Knowledge Sources	Cooperation	X		X	**XX**
	Suppliers	X	X	**XX**	
	Private Clients	X	X	X	**XX**
	Public Clients				
	Competitors				
	Consultants				
	Universities				
	Public Research Centers				**XX**
	Private Research Centers	X			**XX**
	Professional Associations	**XX**	X	X	X

Source: Authors' elaboration.

Exp (β) = 1.536, $p < 0.01$) and private (i.e., *Exp (β)* = 1.414, $p < 0.01$) research centers proved to be crucial for the highest level of eco-innovation radicalness (i.e., eco-effectiveness), and private research centers are also relevant in lower levels of eco-innovation radicalness (component addition [*Exp (β)* = 1.250, $p < 0.05$] and energy efficiency [*Exp (β),* = 1.352, $p < 0.01$]). Finally, the knowledge from professional associations proved to be essential for all the types of eco-innovations, in particular regarding environmental compliance (i.e., component addition) (i.e., *Exp (β)* = 1.610, p = 0.00), materials (i.e., *Exp (β)* = 1.424, p = 0.00) and energy (i.e., *Exp (β)* = 1.534, p = 0.00) efficiency.

Regarding the control variables (Table 2), we observed that small firms (less than 50 employees) were less likely to focus on compliance (i.e., *Exp (β)* = 0.815, $p < 0.01$) and materials efficiency (i.e., *Exp (β)* = 0.800, $p < 0.01$) (contrary to the results of correlation analysis), while large firms tended to pursue materials efficiency (i.e., *Exp (β)* = 1.237, $p < 0.01$), energy efficiency (i.e., *Exp (β)* = 1.208, $p < 0.05$), and radical eco-innovation (i.e., *Exp (β)* = 1.443, $p < 0.01$). The export orientation of the firm performed similarly to correlation analysis and showed that firms which focus on international markets were 42% more likely to focus on compliance (i.e., *Exp (β)* = 1.421, p = 0.00), 34% on material efficiency (i.e., *Exp (β)* = 1.348, $p < 0.01$), 30% on energy efficiency (i.e., *Exp (β)* = 1.297, $p < 0.01$), and 37% on radical eco-innovations (i.e., *Exp (β)* = 1.369, $p < 0.01$). Finally, the results revealed that the importance of different types of eco-innovations might vary based on the industry. For instance, firms from the manufacturing industry were 59% more likely to focus on compliance (i.e., *Exp (β)* = 1.593, p = 0.00), 88% on decreasing the materials use (i.e., *Exp (β)* = 1.883, p = 0.00), and 67% on decreasing the energy consumption (i.e., *Exp (β)* = 1.666, p = 0.00). The firms from the food industry were 70% more likely to search for new solutions to comply with regulations (i.e., *Exp (β)* = 1.700, $p < 0.01$), 56% to increase the energy efficiency (i.e., *Exp (β)* = 1.562, $p < 0.01$), but showed less propensity to pursue more radical eco-innovations (i.e., *Exp (β)* = 0.701, $p < 0.01$). We did not get any significant results for the firms in the agriculture and hospitality industries.

4.4. Robustness and sensitivity tests results

Moreover, we performed robustness and sensitivity tests (see Table 4) to evaluate the structural validity of our main models. The models for component addition and eco-effectiveness proved to be robust and not sensitive to the exclusion of control variables (in concordance with the pseudo-R2 results). However, the models related to eco-efficiency (both materials and energy) demonstrated some degree of variation. We excluded the variables that did not show any significant results, were not robust, and were sensitive to control variables for further analysis.

4.5. The Summary of Results

The summary of our results is presented in Table 5. It includes the results of the main models, adjusted by the results of the robustness and sensitivity tests. The checkmark (X) means that cooperation or a particular external source of knowledge showed significant robust results. The double checkmark (XX) communicates the highest importance of explanatory variables for particular eco-innovation levels of radicalness. The squares in grey report the results that were not significant in the main models or were not robust.

We partially confirm our H1 and state that cooperation is positively associated with all levels of EI radicalness (excluding material efficiency). Our results also fully confirm H2 and show that cooperation is particularly important when firms pursue radical EI (i.e., eco-effectiveness level). Regarding the external sources of knowledge, our empirical tests did not provide any significant and robust results for public clients, competitors, consultants, and universities. Although in some cases, the relationships between a particular knowledge source and different eco-innovation levels are significant in the main models, they are not in the robustness test models; therefore, such relationships are not robust, and thus we discarded them. However, the use of knowledge from suppliers, private clients, and public and private research centers showed a significant and robust positive relationship with various levels of EI radicalness. Finally, the use of knowledge from professional associations showed a significant and robust positive association with almost all the levels of EI radicalness. In the particular case of component addition level, we have to be cautious since the last variable appeared only in the 2016 addition of PITEC, and it was not possible to test the robustness. To sum up, we partially confirm H3 and state that external sources of knowledge are positively related to the different levels of EI radicalness. We also fully confirm H4 since we observed that the importance of external knowledge sources varies according to the levels of EI radicalness.

5. Discussion

This study intended to investigate how certain forms of open innovation approach, such as cooperation and the choice of external knowledge sources, affect various levels of EI radicalness based on the eco-innovation novelty and impact. We discuss the findings in the following section.

First, while the innovation and sustainability literature traditionally distinguish between incremental and radical types of EI (Arekrans et al., 2022; Chadha, 2011; Lin, 2016), our results show that radicalness is not a dichotomous characteristic and should be considered a spectrum (Aragón-Correa, 1998; Hart, 1995). In this study, we adopted a three-level framework of eco-innovation radicalness proposed by Carrillo-Hermosilla et al. (2010) and distinguished between the levels of component addition, eco-efficiency, and eco-effectiveness based on the eco-innovation novelty and impact. Each of the levels showed a unique relationship pattern with cooperation and sourcing external knowledge. Moreover, at the level of eco-efficiency, where organizations seek to increase their environmental performance through more efficient use of resources, there were some minor (but still) differences between material efficiency and energy efficiency. Our results support previous studies that related the radicalness of EI to the various types of environmental strategies (Klewitz and Hansen, 2014). For instance, Aragón-Correa et al. (2008) distinguished between reactive, proactive, and environmental leadership strategies, Noci and Verganti (1999) also offered three-level typology, including reactive, anticipatory, and innovation-based types of environmental strategies. Therefore, we conclude that the binary perspective might be limited to investigate the radicalness of EI, and future research should incorporate more levels for the proper analysis.

Second, our initial literature review revealed an important gap in the literature on OEI in understanding how various forms and modes of OI affect EI in general and the radicalness of EI in particular. For instance, Leitão et al. (2020) tried to compare the relationship between inbound OEI and outbound OEI and concluded that both modes have a positive impact on firms' environmental performance. There is also some evidence of successful crowdsourcing challenges that helped organizations to solve environmental issues (Bogers et al., 2020; Chesbrough, 2012). However, most of the studies use the term OEI as a homogeneous concept and as an umbrella term to refer to cooperation and the flow of knowledge and resources across the boundaries of organizations to develop EIs (Bigliardi and Filippelli, 2022; Chistov et al., 2021; Sanni and Verdolini, 2022). Our results reveal the differences between active cooperation with external organizations from just sourcing external knowledge. Therefore, we conclude that each form and representation of OEI has its own unique characteristics that have to be considered and that may lead to differences in the relationships with various types of EI (i.e., based on the radicalness of EI).

Third, our study expands on the existing literature by providing a more comprehensive analysis of the role of cooperation in driving various levels of eco-innovation (EI) radicalness. While multiple previous studies (De Marchi, 2012; Mazzanti and Zoboli, 2009; Rennings and Rammer, 2011) have established the importance of cooperation in introducing EIs, our investigation offers a more nuanced understanding of its impact across different degrees of radicalness. We found that cooperation was positively associated with nearly all EI levels of radicalness except material efficiency. This result supports previous findings that cooperation is crucial for introducing incremental solutions to comply with basic environmental laws and regulations (i.e., end-of-pipe solutions) (Camisón, 2010; H. Lin, 2016) and for increasing eco-efficiency through reduced energy consumption (Vaiyavuth, 2012). Moreover, we add to the findings of Inigo et al. (2020) and Mothe and Nguyen-Thi (2016) by reinforcing that cooperation is particularly vital when firms aim to introduce more radical solutions to address complex environmental issues (i.e., eco-effectiveness). This distinct insight underscores the essential role of cooperation as a key element of the OEI strategy, not only for developing EI (European Commission, 2013) but also for tackling pressing environmental challenges (Bogers et al., 2020) and effecting systemic changes in the current industrial, economic, and political systems (Curley and Salmelin, 2018; McGahan et al., 2021).

Fourth, while overall, external sources of knowledge were positively associated with all levels of EI radicalness, we found major distinctions regarding the importance of each one when we disaggregated them into individual sources. In spite of the major attention to the role of suppliers in EI and some evidence that supplier integration is positively linked with radical EI (Zhang et al., 2020), our results show that knowledge from suppliers is mostly associated with the end-of-pipe and eco-efficiency solutions, particularly with energy efficiency. This coincides with previous research showing that knowledge sourcing and partnership with suppliers are positively associated with incremental EI but not necessarily with radical EI (Zhang et al., 2020; Zhao et al., 2020). The knowledge from private clients was positively associated with all the levels of EI radicalness, particularly with eco-effectiveness. These results support the seminal studies from the innovation literature that suggest that organizations that have a strong market orientation and that involve their end users and customers in the innovation process are more prompt to develop radical solutions (Narver and Slater, 1990; von Hippel, 2005). Sourcing the knowledge from research institutions was also deemed to be particularly important for more radical EIs. This dynamic can probably be explained by the differences in the type of knowledge that organizations receive from the knowledge partners. As we have already discussed, radical EIs on many levels are more complex than other types of innovations, therefore, they might require very specialized technical knowledge that may be developed exclusively with the experience and infrastructure of research institutions (Belin et al., 2011).

Finally, we also observe the general lack of active cooperation among the firms during the innovation process (only 52.1%) and much less whenever the firm pursues eco-innovation objectives (around 23%). The lack of cooperation has been shown to be one of the major barriers to EI (Polzin et al., 2016). Our results reveal a paradox where cooperation is needed to achieve environmental goals (particularly radical ones), but there is still a big percentage of organizations that do not reach out for knowledge and resources outside their organizational boundaries. This coincides with previous studies that also showed the general lack of collaboration during EI R&D (Chistov et al., 2021). In agreement with other authors, we suppose that while firms may understand the importance of cooperation and OEI in general, they may be hesitant to adopt it due to various internal constraints (the availability of resources, the lack of experience), as well as inherent challenges of cooperation itself (i.e., conflicts of interests, mismatch of common objectives, communication issues, free-riding behavior of partners) (Hermann et al., 2016).

6. Conclusions, limitations, and directions for future research

The aim of this study was to contribute to the literature and overall understanding of OEI by analyzing the effect of an open innovation approach on EI and, in particular, how cooperation and access to external knowledge affect various degrees of EI radicalness based on eco-innovation novelty and impact.

This study has some limitations that might be addressed in future research. First, the context of our sample is limited to Spain. However, our methodology can be easily replicated for all the countries that adopted Community Innovation Survey (CIS). Similar data is available for European countries, India, South Korea, Chile, and Mexico. Also, the results of our study indicated that choosing the sample based on the industry, the size or age of the firm may also impact the relationship between open innovation and radicalness of eco-innovation. While our sample is equally representative of small, medium, and large businesses, most of them are mature firms with more than 40 years of existence. Future studies could use the same methodology to analyze firms in different stages of their development. Second, in our study, we faced limitations related to the choice of indicators to measure the radicalness of eco-innovation. Due to the unavailability of certain variables in the data, we had to rely on proxies as substitutes, which may not fully capture the essence of the original variables. This could potentially impact the accuracy and comprehensiveness of our findings, and further studies may wish to explore alternative indicators or data sources to better measure eco-innovation radicalness. Also, we treated cooperation as a monolithic concept and did not delve into its various characteristics, such as depth and breadth. Future research could explore the diverse aspects of cooperation, assessing how these characteristics may influence the relationship between open innovation strategy and eco-innovation radicalness. Third, while we employed logistic regression in our study, the PITEC database might also be appropriate to employ other statistician methods that offer additional insights. Finally, we base our explorations on the conceptual framework proposed by Carrillo-Hermosilla et al. (2010). While it provides a solid theoretical foundation for our research, it is important to note that multiple frameworks have been put forward in the last decade, each offering distinct perspectives and approaches to studying eco-innovation. As a result, future research may benefit from exploring alternative frameworks or even combining elements from different models to develop a more comprehensive understanding of eco-innovation radicalness and its relationship with open innovation.

This study was motivated by both academic and practical reasons. We hope that the theoretical implications of our research will bring further advancements in the understanding of the role of the open innovation approach in developing eco-innovations, as well as a closer and more detailed investigation of various characteristics, forms, and approaches to OEI. From the practitioners' perspective, we hope that our results provide a framework for organizations to choose the key external knowledge sources and partners based on their EI objectives and to decrease the risk of mismatch between them, thus taking advantage of the positive effects of OEI and avoiding the potential pitfalls. Finally, our results showed the crucial importance of both public and private research centers for more radical EI. Therefore, if policymakers would like to accelerate the transition of countries towards more sustainable modes of operation, they have to take a close look at how to support their research institutions and how to secure their flow of knowledge with the industry.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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