R&D MANAGEMENT

Management of patented 'circular innovation' in view of the circular economy

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This study mainly aims to analyse whether innovation related to the circular economy's principles, defined as 'circular innovation', is closely linked to environmental disclosure and contributes to the generation of improvements in environmental performance. The article also aims to test whether waste patents, as a specific indicator of circular innovation, are more valuable assets that need specific strategic management due to their level of novelty, complexity, and radicalness being higher than other green or conventional innovations. The empirical analysis uses a rich firm-level dataset of worldwide companies for the 2011–2015 period, with 1330 observations to show that environmental disclosure and environmental performance are positively associated with circular innovation. This innovation is in fact, more intensive in patent claims and patent citation generation, indicating a higher economic value for companies. The article contributes to this new line of inquiry on defining circular innovation, as well as providing some environmental determinants and consequences from the stakeholders' perspective in relation to circular business models.

1. Introduction

Policymakers, academics, and practitioners use the concept of the circular economy (CE) to refer to a sustainable model that does not compromise economic growth (Pratt et al., 2016) because it is characterised by efficient flows of resources, waste, energy, materials, labour, and information, thus ensuring that natural and social capital are constantly replenished (Aranda-Usón et al., 2018). In summary, a CE aims to create circular (closed) loops in which raw materials and other resources are used repeatedly in different phases (Yuan et al., 2006).

At a micro-level, the CE provides a compromise between productivity and the sustainable use of resources by transforming the linear economic model into a circular one (Chaves Ávila and Monzón Campos, 2018). A circular business model can be achieved by reducing dependence on raw materials and energy through innovations in response to the CE's complexity with respect to waste minimisation (Ghisellini et al., 2016) and by closing the material loops (Banaite and Tamošiūnienė, 2016).

In this scenario, in which there is planned investment in innovation, we have considered innovation linked to the CE, defined here as 'circular innovation', as a specific eco-innovation aimed at facilitating the shift to a CE (Del Río et al., 2017; de Jesus et al., 2018; Scarpellini et al., 2020). Eco-innovation and circular innovation have the common purpose of environmental improvement, although it should be noted that the latter is more specifically aimed at closing the material flows and achieving the 'Rs transition', as defined by Modic et al. (2021). This fundamental difference makes it essential to perform a specific analysis of circular innovations and related patents (Portillo-Tarragona et al., 2022), something which is of particular interest for companies that are progressively introducing a circular business model (Cainelli et al., 2020).

In this dynamic landscape of the CE, the stakeholders' engagement can contribute in driving circular innovation and its disclosure. Indeed, companies are currently introducing indicators to report on CE-related activities as part of their entire sustainability strategy (Garcés-Ayerbe et al., 2019; Khan et al., 2020; Castro Oliveira et al., 2022), and changes are envisaged for environmental disclosures linked to the CE for corporate social responsibility (CSR) (Marco-Fondevila et al., 2021; Moneva et al., 2023). These changes are in response to the general need for sustainable management, which requires a robust information basis that links corporate actions and outcomes with sustainable development (Schaltegger et al., 2017; Zubeltzu-Jaka et al., 2018), and with investments for waste reduction and recycling in a CE framework (Scarpellini et al., 2020; Marín-Vinuesa et al., 2023).

Some academic studies at a micro-level have approached CE reporting in businesses within a framework of normative, instrumental, legitimate, or reputational strategies in response to stakeholders (Stewart and Niero, 2018; Scarpellini et al., 2020; Marco-Fondevila et al., 2021; Moneva et al., 2023). However, firms' environmental performance and disclosure are still underexplored from a circular perspective, and the theoretical approach to CE in business is still in the incipient stage of analysis in the accounting literature. Only a few empirical studies have explored the theoretical foundation of innovation in the specific CE context (de Jesus et al., 2018; Scarpellini et al., 2020; Portillo-Tarragona et al., 2022), and this study aims to contribute to this line of inquiry.

In the literature, the disclosure of circular innovation has received little empirical support, even though the relevance of a systematic stakeholder's perspective when reporting the CE. Thus, the relation between environmental disclosure and circular innovation in firms is addressed in this study to contribute to a relatively understudied topic in the CE discourse.

Based on these premises, this study mainly aims to define and measure circular innovation (measured by using patents) in businesses to explore the relationship between circular innovation, environmental disclosure, and environmental performance. This study also analyses whether circular innovations are more valuable assets with higher levels of novelty, complexity and radicalness than other green or conventional innovations.

This article does in summary offer a review of the relevant literature in the next section in order to present our research questions. The methodology is described in Section 3, and the results and discussion are summarised in Section 4. Finally, we outline the main conclusions and potential avenues for future research in the last section.

2. Background

Our study addresses the intersection of circular innovation and the environmental disclosure and performance of firms. To achieve this objective, we used a common background regarding the state of knowledge to measure circular innovation at a micro-level, and the literature focuses on firms' environmental performance and disclosure.

2.1. Circular innovation

The shift from a linear growth model to a circular one involves innovation to operate in environments with finite resources (de Jesus and Mendonça, 2018; Arbolino et al., 2020). Innovations are expected in the future for waste recycling and recovery, particularly for production processes and at the end of the product's life cycle (Coenen et al., 2020). Investments in innovation do therefore need to be prioritised from a CE perspective, despite the fact that research focused on the measurement of circular innovations is still being studied. Although scholars are defining and measuring the adoption of CE at a micro-level (Aranda-Usón et al., 2020; Scarpellini et al., 2020), there is an ongoing debate about specific indicators for capturing CE value and the use of patents to this end (Fusillo et al., 2021).

Patents are traditional indicators of innovation, and several authors have highlighted the advantages of using these metrics (Griliches, 1990; Ratanawaraha and Polenske, 2007; Kim and Lee, 2015), but the use of patents to measure circular innovation has been explored by a few authors with some limitations (Fusillo et al., 2021; Modic et al., 2021; Portillo-Tarragona et al., 2022; Marín-Vinuesa et al., 2023). In a first attempt to map the technological evolution of CE technologies as a whole, Fusillo et al. (2021) use patents to investigate the evolutionary patterns within the CE technological change in a spatial context. Modic et al. (2021) state that patents and their additional information provide only partial information, being an indirect output measurement of CE-related innovation. These seminal studies enshrine, as well as discuss, the analysis of patents as a source of information about CE-related innovation. Another analysis of waste-related patents and their relationships with the economic performance in business is offered by Marín-Vinuesa et al. (2020), while Portillo-Tarragona et al. (2022) classify and measure 'circular patents' to bundle them into the companies' innovation capabilities.

Although these previous studies provide specific results in relation to circular innovation through patent analysis, further studies are required to know the impact that this innovation entails. We have therefore extended our analysis to nearby research fields, such as eco-innovation, and we argue that patents can be used to measure circular innovation in a similar way to how patents have been widely used as a proxy to measure eco-innovation (Berrone et al., 2013; Delgado-Verde et al., 2014; Haščič and Migotto, 2015; Fabrizi et al., 2018; Leyva-de la Hiz et al., 2018; Marín-Vinuesa et al., 2020). In the eco-innovation discourse, the number of green patents is used as the output of eco-innovation investments made by companies (Marín-Vinuesa et al., 2020), and here we explore the use of patents as an indicator of circular innovation in business.

An advantage of using patents as indicators to measure a company's innovation activities is that they can be grouped according to different technologies (Lindman and Söderholm, 2016; Rezende et al., 2019). We can therefore assume that circular innovation can be measured through patents registered to protect technology innovations related to the circular model, consistent with previous studies on this topic (Hysa et al., 2020; Modic et al., 2021; Portillo-Tarragona et al., 2022).

From a CE approach, the use of different international classifications allows us to define patents related to the main technological innovation for closing material loops, such as recycling and the use of secondary raw materials (EOI, 2016; Smol et al., 2017; Portillo-Tarragona et al., 2022). Thus, we have focussed our analysis on patents specifically related to waste management as circular innovation indicators at a micro-level, in line with Marín-Vinuesa et al. (2020).

This research field is not without challenges because there is still no consensus on how to measure specific innovations for a CE through patent data, and one of the objectives of this study is to contribute to this debate.

2.2. *Environmental disclosure in a CE model*

Based on several anecdotal examples, environmental disclosure and environmental patenting activities have been historically linked. Important companies such as Patagonia (Matthews, 2021), Tesla Motors (Tesla Blog, 2014), Toyota (2015), Nokia, IBM or Sony (the latter three under the *Eco-Patent Commons* scheme) provide third parties with royalty-free access to their patented innovations on green technologies. This proposal makes it possible to accelerate green technology diffusion and incorporation and makes it easier and faster to innovate and implement processes that improve and protect the global environment (Hall and Helmers, 2013). In addition, Contreras (2019) discusses an important variety of alternative initiatives that reinforce the role of patents in technological diffusion and communication. This anecdotal evidence could be a first sign that companies that are active in environmental disclosure could be more inclined toward patenting their circular innovations as an additional reinforced communication mechanism.

In the following paragraphs, a straightforward approach to stakeholder theory is summarised to outline the research's general scope and provide a better understanding of companies' environmental disclosure practices. As stated by Scarpellini (2022), multiple stakeholders are beyond the firm-centric view of a circular business model and the stakeholder theory is considered because companies seek to maintain their licence to operate and reduce possible gaps between their stakeholders' expectations in terms of corporate sustainability. Moneva et al. (2023) recently confirmed the importance of this theoretical approach to analyse disclosure of CE-related practices and investments in financial institutions for sustainability accounting and reporting.

In recent decades, companies have progressively adapted their environmental strategies to align themselves with social and institutional environments (Gallego-Alvarez et al., 2017), as well as adopting communication strategies to potentially influence stakeholders and societal perceptions (Costa et al., 2019). This evolution requires sustainability innovations and initiatives involving all corporate functions and external stakeholders (Schaltegger et al., 2017). According to Moneva and Llena (2000), stakeholder theory recognises that, besides the traditional users of accounting information (shareholders and creditors), several agents are interested in the environmental behaviour of companies. Consequently, they demand information regarding the impact of their activities on the environment. To the extent that firms recognise the legitimacy of their stakeholders' interests, they tend to increase their environmental information to report voluntarily.

In the CE literature analysing the micro-level, some studies have been founded on the stakeholder theory (Walls and Paquin, 2015), arguing that a company's environmental behaviour in the CE context is influenced by its internal factors and its external environment (Liu and Bai, 2014). Geissdoerfer et al. (2017) and Lieder and Rashid (2016) also highlight stakeholders' importance in companies adopting CE principles, but circular innovation has not been specifically included to date in these investigations from the stakeholders' theoretical perspective.

Previous studies pointed out the involvement of different stakeholders in developing and enabling the circular flow of material and resource efficiency (Jiménez-Rivero et al., 2017; Ranta et al., 2018; Inigo and Blok, 2019; Aranda-Usón et al., 2020). A lack of stakeholder engagement in the CE at a micro-level is highlighted as a constraint that prevents circular projects from becoming successful in practice (Winans et al., 2017; Inigo and Blok, 2019). Moreover, Coenen et al. (2020) argue that stakeholders' participation in circularity discussions increases their awareness and fosters the organisational transition toward CE. The motivation for environmental reporting within the framework of stakeholder theory is undoubtedly considered a major factor in enhancing a company's credibility and reputation (Marco et al., 2019).

We can posit that communication with stakeholders responds to their expectations in terms of sustainability, and that CE offers critical challenges in terms of stakeholder management for environmental disclosure and other environmental accounting and reporting practices (Scarpellini et al., 2020). However, stakeholders' contributions to CE disclosure have seldom been considered from a theoretical viewpoint and have received little empirical support, especially with respect to circular innovation. This study does therefore attempt to partially address this gap by analysing firms that develop circular innovation and their environmental disclosure practices.

Marco et al. (2019) demonstrate significant evidence of a causal relationship between environmental disclosure and eco-innovation and the pivotal role of managers, subject to their strategy, values and level of engagement. Other studies also highlight the influence of eco-innovation on environmental awareness as a key factor in promoting and implementing the concept of sustainable development in society (Severo et al., 2018). In addition, introducing new, environmentally friendly technological solutions contributes to enhancing the green image and reputation of firms, which may positively support the diffusion of these innovations (Chen, 2008).

Based on a bibliographic search in scientific journals[1] related to studies on the circular economy in companies from a stakeholder theory approach, we propose a brief look at previous research in Table 1. We can in summary argue that the debate focused on the relationship between eco-innovation and environmental disclosure is still open, and it can be observed that only a few authors have approached the analysis of firms' environmental disclosure from a CE perspective (Table 1).

From Table 1, we can affirm that the analysis of CE-related patents and environmental disclosure in firms is a relatively understudied topic. It can be seen that the presence of patents is related to the level of disclosure by firms because registering the innovation is a public information channel (Anton and Yao, 2004; Bhattacharya and Guriev, 2006). Furthermore, a high level of disclosure and transparency could encourage the publication of the results of the innovation and, therefore, its patenting. Thus, although we understand that the relationship between circular innovation and environmental disclosure could move in both directions, in light of the most recent studies, we would opt for a positive relationship that delves into the first research question:

Table 1. Previous studies that address the relationship between environmental disclosure and eco-innovation or the CE from a stakeholders perspective

Topic	Studies carried out from the stakeholder's perspective
Eco-innovation and environmental disclosure	(Wagner, 2007; Radu and Francoeur, 2017; Scarpellini et al., 2016; Radu and Francoeur, 2017; Scarpellini et al., 2017; Severo et al., 2018; Yin and Wang, 2018; Marco et al., 2019; Przychodzen et al., 2019)
Circular economy and environmental disclosure	(Brown and Bajada, 2018; Marco-Fondevila et al., 2019; Stewart and Niero, 2018; Aranda-Usón et al., 2020; Scarpellini, 2022; Gunarathne et al., 2021; Marco-Fondevila et al., 2021; Scarpellini, 2021; Benito-Bentué et al., 2022; Castro Oliveira et al., 2022; Moneva et al., 2023; Heras-Saizarbitoria et al., 2023)

RQ1 Do higher levels of environmental disclosure and reporting lead to a higher level of circular innovation in companies?

RQ1 does not entail a new line of research as far as eco-innovation is concerned, but it is original in the specific analysis of patented circular innovation. Once this relationship has been analysed, this study also examines the impact that circular innovation has on companies in terms of environmental performance.

2.3. *Circular innovation and environmental performance*

The technological resources of companies showing high levels of circular innovation include patents related to energy saving in mobile communication systems (Nokia, WO2023011890A1), efficient processes to produce materials for electric car batteries (Tesla Motors, EP4028363A1 or Toyota, US2023051290A1) or new low-weight insulation materials for textile purposes (Patagonia, WO2017020022A1). The technological developments covered by these cases exemplify how environmental-related patents can easily be transformed into environmental performance improvements in these companies. Nevertheless, among the technology-intensive and prolific companies in patent registration, such as those previously mentioned, there are no examples of waste patents for circular innovation. This fact suggests the scarce importance of these environmental advancements in relation to other green technologies, and the need to advance in knowledge and opportunity analysis in this area.

Managers are currently concerned about environmental performance for reasons ranging from regulatory and contractual compliance to public perception and stakeholder pressure (Huang and Li, 2017). In the CE context in particular, some authors argue that environmental performance and disclosure are higher for firms operating in environmentally sensitive industries (Llena-Macarulla et al., 2023).

The environmental benefits derived from circular innovation are mainly linked to technological advantages and environmental performance in terms of waste management and recovery for closing the material loops as the pillar of a CE (Marín-Vinuesa et al., 2023; Salesa et al., 2023).

Previous studies have demonstrated that green patents have implications for reducing emissions at a macro-level (Carrión-Flores and Innes, 2010; Wang et al., 2012; Weina et al., 2016), but these positive impacts are still understudied for circular innovation. Al-Tuwaijri et al. (2004) partially approached this goal by assessing environmental performance in measuring recycled waste. Thus, we can expect that higher levels of environmental performance at firms will drive circular innovation (Castro Oliveira et al., 2022; Zhang et al., 2022; Marín-Vinuesa et al., 2023), but the direction of this relationship needs more investigation for the CE with respect to introducing specific innovations (Scarpellini et al., 2019). Greater introduction of CE-related activities could lead to higher levels of environmental performance. But the relationship could also be the opposite, since the companies that have the best environmental results are the best prepared for the CE; they already demonstrate environmental leadership (Aragón-Correa, 1998). Therefore, despite the intuitive relationship between CE and firms' environmental performance, the impact of circular innovation on reducing the environmental burden must be examined in depth at a micro-level.

Based on these considerations, we propose an empirical analysis of the relationship between circular innovation and companies' environmental performance, because the mere existence of circular innovations does not ensure any improvement in the environmental performance of a company. This therefore leads to the second research question of this study:

RQ2 Do higher levels of circular innovation lead to a higher level of environmental performance at companies?

This second relationship is complex to demonstrate due to the time lag between investments in circular innovation and the consequent impact on the environmental performance of companies. Despite the potential differences in the relationship between investments and impacts experienced in each company, this topic continues to be studied (Scarpellini et al., 2017; Marín-Vinuesa et al., 2023), and we propose to analyse it specifically in the CE environment.

Over the years, questions concerning the economic value of patents have attracted increasing attention from researchers who have used patent value for a variety of purposes, including measuring inventive output, evaluating the incentive effect of patents or determining the contribution of intangibles to the firm's value (Bessen, 2008). In the specific case of circular innovation-related patents, these questions gain even more interest due to the proven interest in the circular innovation of governments and society in general (Xu et al., 2021).

Historically, radical innovations have been related to the economic value of patents because they are successful innovative technologies that break existing paradigms, open new trajectories and represent the basis on which further innovations are built (Shane, 2001; Gupta et al., 2006). Reitzig (2003) states that novelty, inventive activity, complexity and disclosure are major patent value determinants. A higher patent value is an unequivocal sign of the company's wealth through higher intangible assets (Gambardella et al., 2008).

In terms of economic value, it might be assumed that the novelty, complexity and radicalness of innovative technologies underlying sustainability lead to a higher value of patents specifically related to them (Petruzzelli et al., 2011; Popp and Newell, 2012; Dechezleprêtre et al., 2017; Barbieri et al., 2020). These superior characteristics of green technologies are based on three main points of view. First, new environmental technologies require diverse, multi-purpose and systemic knowledge and competencies far beyond the traditional industry knowledge base (De Marchi, 2012; Horbach et al., 2013; Ghisetti et al., 2015). These extra-effort requirements are confirmed by the greater intensity, constantly reconfigured and non-routine skills of green jobs (Consoli et al., 2016). Second, environmental technology advancements should satisfy different and joint objectives such as technological advancement, environmental improvements and economic competitiveness (Oltra and Jean, 2005; Pearson and Foxon, 2012). Third, the superior value of innovation is also related to the capacity to serve as a base for future technological developments and launch new technological opportunities (Schoenmakers and Duysters, 2010). In this sense, green technologies have a greater impact on subsequent technological advancements than other traditional developments (Cecere et al., 2014; Dechezleprêtre et al., 2017). Thus, some previous authors, such as Ardito et al. (2016) or Pearson and Foxon (2012), suggest that green technologies should be considered as a new type of general-purpose technologies which are distinguished by serving as the pivotal point of many future technological developments (Bresnahan and Trajtenberg, 1995; Hall and Trajtenberg, 2004).

Green patents advance technical knowledge evolution, obtaining a higher value than other traditional patents, as some recent scholars have empirically shown. Dechezleprêtre et al. (2017) found that green patents were cited more than traditional and pollutant counterparts. Popp and Newell (2012) attribute a higher social value to alternative energy patents, as they are cited more frequently and by a broader range of technologies than non-green energy patents. Barbieri et al. (2020) found more forward citations in green patents because green technologies are more complex and appear to be more novel than non-green technologies.

In this context, sustainability has often been recognised as a new frontier of innovation (Nidumolu et al., 2009; Cainelli et al., 2015). In 2015, the United Nations (UN) added organisational innovation as a priority to boost the achievement of their sustainable development goals and lead to immediate actions to protect the planet and ensure a more sustainable future scenario. Thus, we could argue that a feature of CE-related technologies, such as those related to the higher level of circular innovation adoption, could be greater needs in terms of complexity and novelty compared with other green technologies, particularly for industrial symbiosis or sharing models (Aranda-Usón et al., 2020).

Furthermore, circular innovation is expected to be more valuable than its green and traditional counterparts, and the previous arguments suggest that circular technologies could demand higher levels of originality, novelty and radicalness.

However, despite the growing interest in these issues, there is still relatively little research into the value of green patents (Chai et al., 2020) and, to the best of our knowledge, previous studies have not approached the value of specific circular innovation measured through patents in a CE context. To explore this line of enquiry, we propose the third research question:

RQ3 Is circular innovation more valuable compared to green innovation?

As a final note in the background analysis, Figure 1 summarises this study's conceptual model.

The following sections summarise and answer the research questions formulated against this background.

3. Research design

3.1. Description of dataset

The empirical analysis of this study is based on a large dataset that includes rich firm-level data on 266 public companies worldwide for the 2011–2015[2] period, and the final sample was integrated for balanced panel data with 1330 observations (five-yearly observations for each of the 266 companies analysed). Data were collected by three databases: (i) EPO-PATSTAT for patent data, (ii) Bloomberg ESG database for environmental disclosure and environmental performance metrics and some control variables and (iii) COMPUSTAT for financial control variables. We have focused

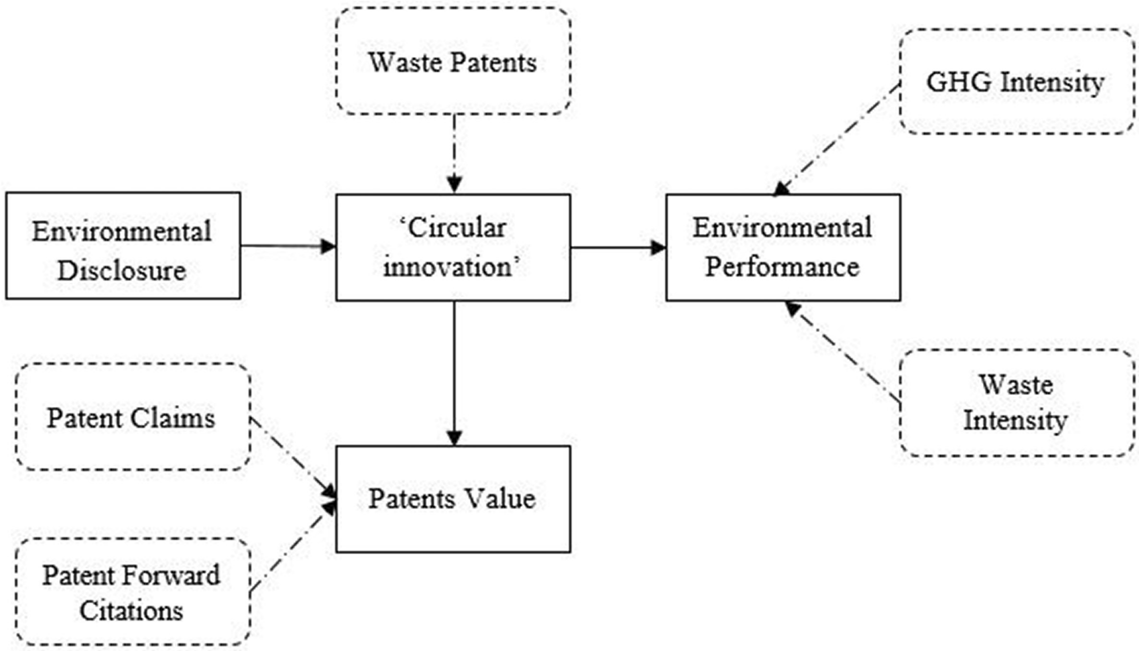

Figure 1. Conceptual model of this study.

Table 2. Sample description

SIC	Industry	*N*	Country	*N*
10	Metal mining	26	Australia	19
12	Coal mining	1	Switzerland	17
13	Oil and gas extraction	33	Germany	12
14	Mining and quarrying non-metallic minerals	2	France	16
20	Food and kindred products	36	UK	25
26	Paper and allied products	6	US	141
28	Chemical and allied products	73	Canada	36
29	Petroleum refining and related industries	14		
30	Rubber and miscellaneous plastics products	4		
31	Leather and leather products	2		
32	Stone, clay, glass and concrete products	4		
33	Primary metal industries	3		
34	Fabricated metal products	6		
49	Electric, gas and sanitary services	56		

only on companies operating within high-polluting industries, where the potential impact of circular innovation is more significant and likely to be evident. The final sample selection was the result of including only companies, from these industries, present on both Bloomberg ESG and COMPUSTAT databases and with accessible data on the key variables pertinent to the study for the 2011–2015 period.

The final dataset includes companies from 14 business-to-business (B2B) high-polluting industries and seven OECD countries (Table 2) to capture processes linked to circular innovation. The companies in the final sample filed 48,946 patents involving 416,119 claims and received 46,557 citations in the analysed period.

This sample is an accurate context in which to explore our research questions. Most of the prolific research on the technological aspects of the circular economy has focused on specific institutional contexts, such as China or the European Union, and specific areas of activity, such as metallurgy or agro-food industries (see Merli et al., 2018 for an updated literature review). Our sample in contrast includes seven countries involving different institutional contexts and 14 high-polluting industries to obtain a more integrative view of circular innovation. Polluting industries were considered in this sample, given their potential to apply eco-innovation and CE-related technologies (Berrone et al., 2013; Aranda-Usón et al., 2020; Scarpellini et al., 2020). We identified polluting sectors by following Berrone et al. (2013), who ranked the total amount of toxic emissions using the US TRI (Toxic Release Inventory) database. Finally, since the use of patents from a single patent office can lead to selection bias (De Rassenfosse et al., 2014), we used the EPO-PATSTAT database, which includes patents registered at the OECD patent offices regarded as the most important (including what is commonly known as the triad: European, United States and Japan Patent Offices) to avoid this bias.

3.2. Variables

Table 3 defines the variables that were used to answer our research questions.

Table 3. Description of variables

Variable	Description of measure	Data source
Waste patents	Binary variable indicating whether the company has successfully registered any green patent related to waste management (Y02W)	PATSTAT
Green patents	Binary variable indicating whether the company has successfully registered any green patent (Y02)	PATSTAT
Patent citations Patent claims	The average number of patent forward citations/claims by patent are calculated using three different methods depending on whether the firm has registered any green patent/waste patent or not: 1. For firms with waste patents: Total number of patent forward citations/claims from waste patents divided by total number of waste patents. 2. For firms with green patents: Total number of patent forward citations/claims from green patents divided by total number of green patents. 3. For firms without green patents: Total number of patent forward citations/claims from non-green patents divided by total number of non-green patents	PATSTAT
Environmental disclosure	Score index (0–100) based on the extent of a company's environmental disclosure	Bloomberg ESG
Waste intensity	Ratio between total waste generated and number of employees	Bloomberg ESG
GHG intensity	Ratio between total greenhouse gas (GHG) emissions and number of employees	Bloomberg ESG
Control variables		
Firm age	Number of years of existence (log transformed)	COMPUSTAT
Firm size	Number of employees (log transformed)	COMPUSTAT
Financial performance	Return on equity (ROE)	COMPUSTAT
Absorptive capacity	Ratio between R&D expenditures and sales	COMPUSTAT and Bloomberg
Industry uncertainty	Standard deviation of the firm's stock market value (Miller et al., 2002; Agle et al., 2006)	Bloomberg
Financial constraints	Ratio between total debts and assets (Gomez and Vargas, 2009)	COMPUSTAT
Environmental policy stringency	Score index (0–100) based on the degree of stringency of the country environmental policy instruments.	OECD2002
Industry	Binary variables for 13 industries (SIC 43 was omitted to avoid overdetermination)	COMPUSTAT
Country	Binary variables for six OECD countries (Canada was omitted to avoid overdetermination)	COMPUSTAT
Year	Binary variables for the years 2011 to 2014 (2015 was omitted to avoid overdetermination)	All Databases

3.2.1. Waste patents

Literature on sustainable innovation is far from obtaining a consensus about what is the most accurate measure of circular innovation. Using patents as a measure of innovation offers objectivity, comparability and availability advantages. The time lag between the technology development and the patent registration guarantees that circular technologies have been incorporated into the company when the technology has been patented. Recently, some authors have advanced in the identification of circular innovation-related patents by using the Cooperative Patent Classification (CPC) (Fusillo et al., 2021; Eurostat, 2022). CPC was developed in 2013 and distinguishes between green patents by using a reliable and objective measure. The CPC was a joint project of the EPO (European Patent Office) and USPTO (United States Patent and Trademark Office) to review the IPC, adding a new 'Y' section for tagging emerging technologies, such as those for mitigation or adaptation with respect to climate change (Y02 sub-category).

Based on these premises, we used CPC to distinguish first of all between green and non-green families of patent applications based on EPO (2013) and in line with Veefkind et al. (2012), Valero-Gil et al. (2023) and Fusillo et al. (2021),[3] among others. Additionally, we classified waste patents by using the Y02W CPC sub-category related to climate technologies for waste management. Moreover, based on the argument that waste patents are precisely aligned with the circular model, we constructed a dichotomic circular innovation proxy to select companies that held waste patents filed during every year of our study period (2011–2015). Table 4 shows some interesting descriptive statistics.

Patent data were obtained from the worldwide patent database PATSTAT (version 2016), provided by the EPO. The PATSTAT contains data on more than 100 million patent documents from developed and developing countries (European Patent Office, 2016). It specifically covers 105 patent offices in the triad of the USPTO, EPO and the Japan Patent Office (JPO), making it one of the world's most comprehensive patent databases.

With respect to patent value, previous studies analysing green patent value used forward citations, indicating that the cited patents provided access to a technologically successful line of innovation (Petruzzelli et al., 2011; Dechezleprêtre et al., 2017; Barbieri et al., 2020). Like academic texts, a patent can be cited as a prior art from another patent, and this is a forward citation. Patent citations allow a patent examiner to search for a patent before identifying any prior disclosures of the patent or any similar technology.

In the innovation literature, the number of claims is found to be positively correlated with the monetary value of patents because of their major role in the legal protection process of innovations (Gambardella et al., 2008; Suzuki, 2011). Patent claims define which subject matter is protected or seeks to be protected by patent applications. More claims result in more extensive legal protection, and they are of utmost importance during litigation processes.

The number of forwarding citations and claims is found to be positively correlated with the monetary value of patents, defending their use as proxies (Malewicki and Sivakumar, 2004; Gambardella et al., 2008; Suzuki, 2011). Forward citations indicate that cited patents enable a technologically successful line of innovation, as they contain critical technological advancements (Bessen, 2008; Petruzzelli et al., 2011; Jiang et al., 2019). Patent claims delineate the boundaries of property rights and define the essential novel features of inventions in their broadest form (Lanjouw and Schankerman, 2001). We did as a result use both indicators in this study, the number of claims and the forward citations, to reflect the expected economic value of a patent (Tong and Frame, 1994; Lanjouw and Schankerman, 2001, 2004; Hall et al., 2005). Furthermore, we used the number of citations when realising our analysis and controlled our statistical analysis to show that older patents were likely to have more citations, considering that forward citations can grow over time.

3.2.2. Environmental disclosure

Our study uses the environmental disclosure score from the Bloomberg ESG database to measure the quantity and quality of the environmental information reported and the transparency levels maintained by companies in our sample, in line with other authors (e.g. Arayssi et al., 2016; Baldini et al., 2018; Yu et al., 2018). The Bloomberg ESG database covers more than 11,700 companies in 102 countries and is organised into more than 1300 ESG fields (Bloomberg Professional Services, 2020). The environmental disclosure indicator is based on the extent of a firm's environmental information revealed in its published material. The score is a weighted average disclosure score that considers the effectiveness of the reported environmental engagements rather than the volume of disclosed information. Bloomberg analysts evaluate data based on essential environmental categories, such as energy, green house gases (GHGs), water and

Table 4. Descriptive statistics and correlations*

	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Waste patents	0.08	0.27	1.00												
2. Green patents	0.22	0.41	0.60	1.00											
3. Environmental disclosure	31.93	18.63	0.17	0.28	1.00										
4. Waste intensity	4198.85	13573.58	−0.10	−0.12	−0.05	1.00									
5. GHG intensity	858.61	1734.66	−0.10	−0.13	−0.14	−0.06	1.00								
6. ROE	0.20	2.43	0.00	0.00	−0.05	−0.11	−0.09	1.00							
7. Firm size	30.89	41.03	0.09	0.22	0.14	−0.10	−0.15	0.01	1.00						
8. Firm age	37.86	33.92	0.16	0.17	0.23	−0.14	−0.11	−0.02	0.12	1.00					
9. Industrial uncertainty	0.58	3.82	−0.03	−0.05	0.04	−0.03	−0.01	0.00	−0.02	0.07	1.00				
10. Financial constraints	35.24	179.38	−0.01	−0.03	−0.03	−0.02	−0.01	0.00	0.07	−0.02	0.00	1.00			
11. Absorptive capacity	0.05	0.15	−0.01	0.02	0.14	−0.09	−0.14	0.03	−0.04	0.03	−0.03	−0.01	1.00		
12. Env. policy stringency	2.88	0.60	0.04	0.02	0.19	0.07	−0.14	−0.02	0.09	−0.05	−0.05	−0.01	−0.06	1.00	
13. Patent claims	312.87	977.65	0.40	0.44	0.23	−0.11	−0.13	0.00	0.15	0.13	−0.04	−0.03	0.05	0.01	1.00
14. Patent citations	35.02	161.47	0.24	0.34	0.15	−0.08	−0.08	0.00	0.09	0.05	−0.03	−0.02	0.06	−0.08	0.56

*Absolute values higher than 0.05 are significant at the 5% level.

waste. Each data point is weighted in terms of importance, and the score is tailored to different industry sectors. Each company is only evaluated therefore by considering the relevant data.

3.2.3. Environmental performance

From a CE perspective, we used two different metrics to capture companies' environmental performance, and linked to the introduction of CE-related technologies. The literature has historically used different proxies to measure the environmental performance of a firm, such as expenditure on pollution-control technologies, emission of toxic substances, number of spills or accidents, lawsuits, rewards, implementation or adoption of environmental management standards, or different rankings produced by independent agencies or experts (King et al., 2005). We followed previous authors to analyse the relationship between patent activity and environmental performance, using toxic emissions as an environmental performance measure (e.g. Carrión-Flores and Innes, 2010; Carrión-Flores et al., 2013; Huang and Li, 2017). In particular, we used both GHG emission intensity and waste generation intensity due to their relationship with the CE's primary goals. Higher levels of both indicators indicate lower environmental performance.

3.2.4. Control variables

As in previous studies, our models control several variables to isolate the external effects affecting our main framework. The firm's experience can influence environmental disclosure and environmental performance in its decision to register a patent. Thus, we include the firm's age as a control, following some previous related studies (Marin, 2014; Amore and Bennedsen, 2016).

Some authors also suggest that size can influence the number of green patents (Brouwer and Kleinknecht, 1999; Dernis and Guellec, 2001). We specifically included this control variable because size is considered an important feature of firms transitioning from a linear model to a circular one, and it facilitates eco-innovative processes (Wagner, 2007; Scarpellini et al., 2020). Our model does in addition include financial performance, which is consistent with previous studies that found a positive relationship between corporate environmental management and financial performance (Albertini, 2013). In fact, several authors have included it as a control variable (e.g. Aguilera-Caracuel and Ortiz-de-Mandojana, 2013; Berrone et al., 2013; Aragon-Correa and Leyva-de la Hiz, 2016).

From another perspective, we included in the analysis the level of research and development

(R&D) that is often considered in the literature when measuring innovation (Hagedoorn and Cloodt, 2003; Oltra et al., 2010). Berrone et al. (2013) trust R&D expenditure as the primary input of the patent development process, while other authors measure innovative capacity by using R&D expenditure (e.g. Wagner, 2007; Carrión-Flores and Innes, 2010; Carrión-Flores et al., 2013). In addition, R&D intensity has historically been used as a proxy to measure absorptive capacity (Cohen and Levinthal, 1990), which could influence the patent decision-making process (Pace and Miles, 2020).

We also included the level of financial constraints among the control variables (Mina et al., 2021), since it is expected that companies with slack resources would invest more in the patent-obtaining process. The availability of financial resources can be decisive in the decision to patent new environmental technologies (López-Gamero et al., 2008; Gomez and Vargas, 2009; Scarpellini et al., 2018; Marín-Vinuesa et al., 2020), as well as the fact that the relationship between eco-innovation and financial performance (Leyva-de la Hiz et al., 2018). Aranda-Usón et al. (2019) demonstrate the influence of financial resources on CE introduction in businesses. Uncertainty is consistently regarded as a primary factor influencing eco-innovation and environmental strategies (Aragón-Correa and Sharma, 2003; Rothenberg and Zyglidopoulos, 2007). Based on these previous studies, companies are more likely to invest in environmental resources and adopt environmental innovations when exposed to uncertain environments. The environmental regulation to which firms are exposed could therefore be crucial in moving toward different eco-innovation strategies (Horbach et al., 2012).

Finally, we established controls for potential patent differences between sectors, depending on the nature of the technology (Cohen et al., 2000) or the polluting intensity (Berrone et al., 2013). Moreover, patent activity and environmental behaviour differ between countries, possibly attributable to country-specific institutional matters (Johnstone et al., 2010; Goetzke et al., 2012). In models involving forward citations, we established controls for a year because they are time-dependent, meaning older patents are likely to have more citations.

3.3. Statistical analysis

In trying to offer an empirically supported answer for RQ1, we first ran the specification (1):

$$Waste\ Patents_{it} = \beta_0 + \beta_1\ Environmental\ Disclosure_{it-1} + \beta_2\ Controls_{it} + \epsilon'_{it} \quad (1)$$

Specification (2) helps us by answering RQ2:

$$Environmental\ Performance_{it} = \beta_0 + \beta_1\ Waste\ Patents_{it-1} + \beta_2\ Controls_{it} + \epsilon'_{it} \quad (2)$$

Finally, we conducted the analysis in two stages to explore RQ3: first, we only examined firms with any registered patent, and the relative value of green patents by running specification (3) and using the green patent dummy variable as an independent variable:

$$Patent\ value_{it} = \beta_0 + \beta_1\ Green\ Patents_{it} + \beta_2\ Controls_{it} + \epsilon'_{it} \quad (3)$$

Secondly, we focused on firms with any registered green patent to analyse the relative value of waste patents, and we ran specification (4) using the waste patent dummy variable as an independent variable:

$$Patent\ value_{it} = \beta_0 + \beta_1\ Waste\ Patents_{it} + \beta_2\ Controls_{it} + \epsilon'_{it} \quad (4)$$

We used waste intensity and GHG emission intensity as environmental performance-dependent variables in specification (2) and patent claims and patent citations as patent value-dependent variables in specifications (3) and (4). Control variables included in all the specifications are defined in the previous section. To reduce endogeneity problems connected to reverse causality, we lagged the explanatory variables in specifications (1) and (2) by one year. Additionally, in order to guarantee that our estimations were consistent and did not suffer from endogeneity problems, we ran additional tests for endogeneity. The Durbin–Wu–Hausman chi-squared statistic (0.401, $P>0.100$, Wooldridge (2010) and the Davidson and MacKinnon (1993) test, 0.392, $P>0.100$) confirm that the endogeneity is not a serious problem in our estimations.

Table 5. Regression analysis results

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
	Waste patents	Waste intensity	GHG intensity	Patent claims	Patent citations	Patent claims	Patent citations
Environmental disclosure	0.970 *** (3.787)						
Waste patents		0.011 (0.410)	−0.047** (−2.319)			0.027*** (3.074)	0.046** (1.960)
Green patents				0.098*** (3.850)	0.257*** (3.958)		
ROE	0.068 (1.464)	−0.037*** (−3.276)	−0.025** (−2.149)	−0.004 (−0.541)	−0.018 (−0.610)	1.215 (1.093)	−1.477* (−1.946)
Firm size	0.217 (0.953)	0.029 (0.991)	−0.070** (−2.474)	0.134* (1.682)	0.082* (1.903)	−0.106 (−0.915)	−0.049 (−1.395)
Firm age	0.702** (2.319)	−0.035 (−0.974)	−0.020 (−0.528)	0.030 (0.204)	0.013 (0.151)	0.153** (2.039)	0.030 (0.638)
Industrial uncertainty	−1.556 (−0.967)	0.020 (0.812)	−0.022 (−1.466)	−0.008 (−0.715)	0.005 (0.321)	−0.068 (−0.829)	−0.098 (−0.725)
Financial constraint	−1.992 (−0.597)	−0.332 (−1.140)	0.063 (0.234)	−0.871 (−1.150)	−2.031** (−2.241)	−0.305 (−0.810)	−0.068 (−0.066)
Absorptive capacity	−0.564 (−0.918)	−0.067** (−2.570)	−0.056* (−1.706)	0.015 (0.779)	0.065* (1.761)	0.009 (0.566)	0.195*** (3.692)
Env. policy stringency	−0.374 (−0.607)	−0.106 (−1.312)	−0.049 (−0.989)	−0.186*** (−2.781)	0.055 (0.309)	0.125* (1.884)	−0.041 (−0.245)
Sector dummies	Yes**	Yes***	Yes***	Yes***	Yes***	Yes	Yes***
Country dummies	Yes**	Yes**	Yes***	Yes**	Yes**	Yes	Yes
Year dummies	–	–	–	–	Yes***	–	Yes***
Log pseudo-likelihood	−129.07	–	–	–	–	–	–
LR test (χ^2)	11.25***	–	–	–	–	–	–
$\Delta\%R^2$	–	2.17	1.27**	4.89***	3.70***	0.17***	0.17**
Observations	627	1005	1005	584	584	262	262

Z-scores are reported in parentheses.
*$P<0.10$,
**$P<0.05$,
***$P<0.00$.

To avoid the problem of unobservable heterogeneity, we used a logit[4] estimation with panel data to estimate specification 1 and a random-effects GLS estimation with panel data for specifications (2)–(4), confirmed by Breusch and Pagan's (1980) Lagrangian multiplier test for random effects ($P<0.000$) (Arellano, 2003).

Although the correlation between the independent variables (Table 5) was moderate in most cases, we tested for potential multicollinearity before estimating the regression models. We found that the variance inflation factor computed for all explanatory variables used in the regression analysis was below 5.72, confirming the absence of multicollinearity problems in our models (Barnett et al., 1975).

4. Main results and discussion

4.1. Results

The correlations resulting from the empirical analysis are shown in Table 4. It was observed that the level of environmental disclosure, patent forward citations and patent claims were positively correlated with the presence of waste patents, whereas both GHG emissions and waste generation intensity were negatively correlated.

Table 5 includes the estimations from the regression analysis and confirms our preliminary descriptive results. The likelihood ratio test ($P<0.000$) in Model 1 and the significant increments ($P<0.000$)

in R^2 coefficients in Models 3–7 showed that our independent variables added significant information about the base model, only considering the influence of the control variables. In this regard, the effect of the control variables on the dependent variables remained stable when the independent variables were added.

Regarding RQ1, our results in Model 1 show that the higher the level of environmental disclosure, the higher the existence of circular innovation (β=0.970, 95% CI=[0.920, 1.020]; P=0.000), in response to RQ1. Thus, we can state that companies with more environmental disclosure are more willing to register circular innovation patents because both coefficients are negative and the confidence interval is strictly negative.

In empirically analysing RQ2, Model 2 fails to show a significant environmental performance improvement in terms of waste intensity (β=0.011, 95% CI=[−0.044, 0.066]; P=0.682), while Model 3 confirms how circular innovation is related with higher levels of environmental performance, but only in terms of GHG intensity where the confidence interval is strictly positive (β=−0.047, 95% CI=[−0.086, −0.008]; P=0.020). This evidence helps us to confirm that counterintuitively circular innovation improves environmental performance relative to climate change (GHG emissions), but not in terms of waste generation intensity.

To answer RQ3, as observed in Models 4 and 5 estimations, green patents have a positive influence on patent value because the estimated coefficients in average patent claims, Model 4 (β=0.098, 95% CI=[0.049, 0.147]; P=0.000), and in average patent citations, Model 5 (β=0.257, 95% CI=[0.130, 0.384]; P=0.000), are strictly positive with respect to the confidence interval.

Finally, Models 6 and 7 confirm that the waste patents indicator has a positive influence on the patent value because the estimated coefficients in average patent claims, Model 6 (β=0.027, 95% CI=[0.009, 0.045]; P=0.002), and average patent citations, Model 7 (β=0.046, 95% CI=[0.000, 0.093]; P=0.050), are positive, and the confidence interval is strictly positive. This confirms the pre-established evidence that green patents are more valuable than traditional ones. These results also indicate that companies filling circular innovation obtain more value from their patents than their non-green patent counterparts.

4.2. Additional robustness tests analysis

We have considered alternative measures for circular innovation and additional tests for RQ3 to confirm the suitability and robustness of our previous analysis in answering our research questions. Table 6 presents a replication of Models 1–3, using new variables for waste patents by measuring: (i) the total number of waste patents granted every year (Models 8–10); (ii) a cumulative count of patents, taking into account the number of waste patents granted in the year, and in the previous years in the window of observation (Models 11–13) and (iii) a moving average in the number of patents granted in the year of observation and in the previous one (Models 14–16). In all the new estimations, our additional results guarantee the suitability of the associations presented previously, confirming that environmental disclosure precedes circular innovation and that this, in turn, positively impacts environmental performance related to climate change (GHG emissions).

In terms of additionally proving that circular innovation is more valuable than green innovation, we conducted two ANOVA tests to confirm if there was any significant difference in the patent's average value in relation to the patent groups. In this preliminary analysis presented in Table 7, we found that, on average, companies with waste patents is the group with the highest numbers of forward citations per patent (F=59.12; P=0.000) and claims per patent (F=128.44; P=0.000).

4.3. Discussion

This study makes several contributions that are worth of discussion. First, it contributes to the literature on the measurement of circular innovation in a CE context, using patents and reflecting on their value. Second, this research seeks to better understand how to enhance environmental disclosure for CE, providing theoretical reasoning by drawing on stakeholder theory. Finally, these results are also insightful for empirically analysing the relationships between companies' investments in circular innovation and their environmental performance.

With respect to the measurement of circular innovation, we combine the eco-innovation literature with the CE discourse due to the initial stage of specific literature. Eco-innovations and more specific circular innovations are required to transform linear and inefficient productive patterns into new sustainable circular systems founded on circular flows and zero waste strategies (Scarpellini et al., 2020; Portillo-Tarragona et al., 2022), and they have to be measured to be reported to the main stakeholders. In this respect, the study enhances knowledge about the measurement of circular innovation by using waste patents as a variable proxy, based on the application

Table 6. Robustness additional analysis I

	Number of patents			Cumulative number of patents			Moving average of #patents		
	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13	Model 14	Model 15	Model 16
	Waste patents	Waste intensity	GHG intensity	Waste patents	Waste intensity	GHG intensity	Waste patents	Waste intensity	GHG intensity
Environmental disclosure	0.080***			0.265**			0.068**		
	(0.030)			(0.132)			(0.033)		
Waste patents		−0.003	−0.068***		−0.003	−0.022**		−0.045	−0.103***
		(0.030)	(0.023)		(0.011)	(0.009)		(0.052)	(0.038)
ROE	0.003	−0.037***	−0.025**	0.000	−0.037***	−0.025**	0.001	−0.033***	−0.032***
	(0.003)	(0.011)	(0.011)	(0.003)	(0.011)	(0.012)	(0.001)	(0.006)	(0.004)
Firm size	0.015	0.029	−0.071**	0.047	0.029	−0.071**	0.019	0.010	−0.073**
	(0.018)	(0.029)	(0.028)	(0.065)	(0.029)	(0.029)	(0.020)	(0.033)	(0.035)
Firm age	0.083*	−0.033	−0.019	0.378***	−0.033	−0.021	0.081**	−0.043	−0.044
	(0.044)	(0.036)	(0.038)	(0.144)	(0.036)	(0.038)	(0.040)	(0.040)	(0.044)
Industrial uncertainty	−0.012**	0.019	−0.022	−0.011	0.019	−0.022	−0.003	0.016	−0.020
	(0.006)	(0.024)	(0.015)	(0.010)	(0.024)	(0.015)	(0.002)	(0.023)	(0.017)
Financial constraint	−0.199	−0.331	0.058	−0.404	−0.333	0.048	−0.221	−0.589**	0.049
	(0.140)	(0.291)	(0.269)	(0.281)	(0.292)	(0.268)	(0.146)	(0.289)	(0.354)
Absorptive capacity	0.012	−0.067***	−0.057*	0.033	−0.067***	−0.056*	−0.009	−0.099***	−0.072*
	(0.036)	(0.026)	(0.032)	(0.051)	(0.026)	(0.032)	(0.086)	(0.033)	(0.043)
Env. policy stringency	−0.001	−0.107	−0.048	0.080*	−0.108	−0.052	0.000	−0.171	−0.054
	(0.026)	(0.081)	(0.050)	(0.042)	(0.081)	(0.050)	(0.016)	(0.107)	(0.059)
Sector dummies	Yes	Yes***	Yes***	Yes**	Yes***	Yes***	Yes	Yes***	Yes***
Country dummies	Yes	Yes**	Yes***	Yes	Yes**	Yes***	Yes	Yes**	Yes***
$\Delta\%R^2$	0.61***	2.22	1.39***	2.14**	2.24	1.20***	2.65**	2.31	1.94***
Observations	764	1005	1005	764	1005	1005	544	734	734

Robust standard errors are reported in parentheses.
*$P<0.10$,
**$P<0.05$,
***$P<0.00$.

Table 7. Robustness additional analysis II

	Companies	%	Observations	%	Patent claims*	Patent citations**
Without patents	96	36	711	53	–	–
Patents – No GP, No WP	68	26	332	25	0.60	23.64
Green patents (GP) – No WP	55	21	197	15	0.92	40.22
Waste patents (WP)	47	18	90	7	1.89	65.36
Total	266	100	1330	100		

*ANOVA Test: $F = 128.44$, P-value <0.000,
**ANOVA Test: $F = 59.12$, P-value <0.000.

in previous studies of green patents as a proxy for eco-innovation (Scarpellini et al., 2019; Marín-Vinuesa et al., 2020) and for circular patents in line with Marín-Vinuesa et al. (2020), Modic et al. (2021) and Portillo-Tarragona et al. (2022).

In summary, we argue that current trends in the introduction of the CE in businesses have systemic conditions that correspond to those experienced with eco-innovation to analyse the relationship between circular innovation and environmental performance and disclosure. Our findings corroborate the results obtained by Marco et al. (2019) for eco-innovation, demonstrating the relationship between waste patents and environmental disclosure in companies, confirming that transparent organisations tend to register patent circular innovations. However, although these results are consistent with the eco-innovation discourse, only a few authors have explored the use of patents as an indicator of CE at a micro-level, with fragmented and discordant results.

In our empirical analysis, we consider that the patents registered by companies are currently viable and suitable indicators to be classified for the measurement of CE, as specific measurement systems have not been developed. Based on our analysis, we lean positively toward the use of patents to measure circular innovation, contradicting the criticism of Cainelli et al. (2020) and reinforcing the favourable positions of other authors (Rocchetti et al., 2018; Smol and Kulczycka, 2019; Hysa et al., 2020; Castro Oliveira et al., 2022; Zhang et al., 2022; Marín-Vinuesa et al., 2023).

In this context, Brown and Bajada (2018) indicate the limited development of informative environmental performance indicators attributable to the technical and institutional constraints applied in the field (Bebbington and Gray, 2001; Burritt, 2004; Gray, 2010; Unerman et al., 2010). We develop adequate metrics in this study for circular reporting, based on existing indicators to be used for specific disclosures in a CE model in which environmental issues have a material impact (Scarpellini et al., 2020). This study does therefore analyse the relationship between circular innovation and environmental disclosure to confirm that firms' efforts to inform and obtain recognition by stakeholders for closing the material loops do indeed facilitate patenting. From a theoretical perspective, it was not our intention to revisit the stakeholder theory in a CE context. Previous studies that highlight the involvement of stakeholders in the swift of reporting forward of a circular model (Reike et al., 2018; Stewart and Niero, 2018; Scarpellini, 2022; Heras-Saizarbitoria et al., 2023) bring our analysis closer to results achieved by Aranda-Usón et al., 2022 when analysing environmental disclosure in the framework of the circular sustainability accounting. We did therefore aim to enhance the knowledge on how to measure circular innovations that have to be reported to stakeholders by firms in order to ensure their joint support for successful CE implementation (Lieder and Rashid, 2016). Recent studies, such as those by Heras-Saizarbitoria et al. (2023) suggest that the CE concept is often used to impress stakeholders, but specific reporting practices focused on CE-related activities are still very scarce. Aranda-Usón et al. (2020) demonstrated that reporting in terms of CE responds to higher levels of CE adoption by companies and is related to stakeholders' pressure. The debate has however been opened about the evolutions of environmental disclosure for the CE and related reporting practices. Thus, when analysing CE-related patents, we propose an extended analysis of environmental disclosure linked to circular innovation that needs more confrontation.

From another perspective, this study is insightful to those interested in the debate focused on environmental performance linked to the introduction of CE in businesses. We confirmed that companies have better environmental performance if they are more willing to register waste patents. Thus, the intuitive idea that higher levels of environmental performance are related to circular innovation in businesses has also been approached in this study from a Stakeholders' perspective. However, further studies are requested about this relationship when CE has been adopted to a large extent by companies, given that in our model the environmental performance is taken in a short time lag with respect to waste patents. In this context, Brown and Bajada (2018) indicate the level of engagement with sustainability practices that arise as a result of constructing and reporting sustainability metrics in a circular supply network. However, the debate over the relationship between circular innovation and environmental performance and disclosure remains open from a Stakeholder's perspective, and more evidence is necessary to validate the adverse effects of legitimising disclosure as pointed out by some authors (Patten and Shin, 2019). To our knowledge, this is the first attempt to empirically demonstrate this relationship in a CE context based on this theoretical framework, and we have opened up a line of inquiry that needs to be explored by academics.

In this study, we have in addition extended the efforts of previous authors, such as Popp and Newell (2012), Barbieri et al. (2020) and Dechezleprêtre et al. (2017) to empirically analyse green patent value. We have in particular complemented the forward citations measure with the number of patent claims to show that waste patents are more valuable than other green patents, especially non-green patents, in terms of both indicators.

5. Main conclusions

The introduction of CE at a micro-level promises to be an effective model to facilitate firms' pursuit of environmental sustainability. However, investigations regarding the effectiveness of environmental disclosure and performance for the introduction of CE in business are still at an emerging stage in the CE literature.

To overcome this gap, this study approaches the use of waste patents as a proxy to measure the introduction of innovation for CE and contributes to the debate about the limits of patents in this type of measurement. We have in addition provided a starting approach for the analysis of relationships between circular innovation, environmental performance and disclosures in companies.

This study can facilitate the measurement of business activities in a CE context and the influence of its environmental performance in supporting decisions about investments in circular solutions for closing material loops. Our results complement prior findings in circular patents, using firm-level data as indicators to measure innovations in a CE context and their impact on environmental performance in terms of waste and GHG intensity. A starting point has therefore been provided for academics interested in studying the determinants of circular innovation at firms and its strategic management. This debate, which has already been developed for the eco-innovation discourse, has now been revisited in a circular scenario.

The analysis of the relationship between circular innovation and environmental performance in terms of GHG intensity and disclosure also provides benchmarks to stakeholders regarding improved sustainability targets in a CE context. These results do in addition support managers, decision-makers and policymakers in defining, measuring, and reporting CE-related investments in intangible assets. Managers realise the importance of environmental disclosure practices and their general environmental performance as practices related to circular innovation. As environmental performance and disclosure have a relationship with investments in patenting circular innovation, they may alter their strategies to register more patents directly related to the proximity of the material loops.

The findings of this research have answered the original research questions. However, our study did have some limitations. This research tried to cope with the limited number of companies included in the sample by including a broader typology of patents from different sectors and geographical locations. Furthermore, the primary source of patent information is also subject to limitations, since it has been limited to a timeline prior to the broader introduction of CE in companies for the period 2011–2015. There were in addition some previous critics about the low reach of our methodology in identifying circular-related patents (Modic et al., 2021). These limitations were minimised by a detailed analysis of the patents' CPC and by generating an unedited database through different sources for this analysis. The data do in addition provide interesting information given the long-term period that patenting entails for companies and given the primary objective of analysing firms' accumulated intangible assets for CE. Nevertheless, future research could confirm our results by using new methods for circular innovation detection and updated databases. Additionally, despite the use of patents to measure circular innovation, further analysis is required to overcome the time lag between investments in circular innovation and the potential temporal disparate impact on the environmental performance of companies.

Despite the limitation of performing analysis after more than 5 years, these results can be considered a first approximation to circular innovation and its impacts on companies and can be compared in the future after CE has been widely introduced. in companies and a greater number of specific indicators are available.

The significant relationship between environmental disclosure and waste patents indicates the need to set some standards concerning enhanced circular innovation measurement and related environmental disclosure. The overall metric used in this study to measure environmental disclosure (as captured by Bloomberg scores) may not adequately capture the disclosure specifically related to waste management and CE in general. Thus, a possible direction for further research is to assess companies' reporting, including informal communication channels, in order to analyse their environmental disclosure of the overall CE arguments.

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Conflict of interest statement

The authors declare no conflict of interest, and they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability statement

Data sharing does not apply to this article. In any case, the data that support the findings of this study are available from the corresponding author upon reasonable request as no datasets were generated or analysed during the current study.

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Notes

[1] An advanced search was performed using the terms "circular economy" and "patents" on the Web of Science core collection on business research-oriented context and excluding conferences proceedings or book reviews. As only a few specific results were found, the term "innovation" instead was used instead of "patents" in a second search. Thus, the main results were analysed based on previous studies related to these topics.

[2] In view of the time required to complete the patent application process, it is reasonable to limit the period under consideration up to the year 2015, as other studies related to patenting in CE have also suggested (Fusillo et al., 2021).

[3] According to Dernis and Guellec (2001), the same patent could be registered in several offices to increase its geographic range of protection. Since we use patent applications from different patent offices, the variable family of patents unifies different applications with the same invention, mainly to avoid patent duplication in our sample.

[4] Logistic regression was used to model binary outcome variables (Long, 1997; Hosmer and Lemeshow, 2000). We used this generalisation due to the dichotomic character of our dependent variable representing the patented circular eco-innovation (waste patents).

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