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Transition towards circular economy: Exploiting open innovation for circular product development

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ABSTRACT

Product innovation is a relevant aspect to consider when transitioning towards a circular economy. However, product innovation encounters several barriers that must be overcome. This article explores how companies exploit open innovation practices to overcome barriers while developing circular products. To address this research gap, the study employs a multiple case-study approach of four companies in the manufacturing sector. Two of them operate in European industrialized regions, and other two operate in less developed regions of South America, emphasizing the need for context-specific approaches to circular economy implementation and circular product development. Our results show that, among other barriers, technical ones, including material quality concerns and a lack of skills, represent significant obstacles in both contexts. In addition, among the open innovation practices, the inbound ones, such as sourcing external knowledge and ideas, support companies to overcome these technical challenges, by leading to more innovative and higher-quality products, enhanced reputation, collaboration, and cost reduction. Consumer co-creation is especially crucial for stakeholder engagement and aligning practices with sustainability goals. Finally, collaboration with universities mostly benefits highly industrialized regions and is recommended for acquiring essential capabilities for successful circular product development. From a theoretical perspective, our study contributes to emphasize the relationships between circular economy and open innovation, as well as region-specific circular economy challenges. From a managerial perspective, we show how inbound open innovation practices can aid circular economy implementation, fostering external knowledge and innovation.

Introduction

In recent years, the shift from linear production to circular economy (CE) practices has emerged as one of the most promising paths towards sustainable development (Aibar-Guzmán et al., 2022; Centobelli et al., 2020; Chirumalla et al., 2024). However, the CE definition varies among scholars (Velenturf & Purnell, 2021), resulting in diverse interpretations. Kirchherr et al. (2017) found that CE often focuses on reduce, reuse, and recycle, neglecting systemic transformation, sustainable development links, and social equity, prioritizing economic and environmental aspects. Aligned, Enciso-Alfaro & García-Sánchez (2024) argue that the CE offers a promising approach that intertwines the sustainable growth of business activities with the protection, restoration, and conservation of ecosystems and their unique natural resources. This study adopts a holistic view, considering CE as a systemic approach that encompasses reduce, reuse, and recycle practices, linking them to sustainable development and prioritizing economic, environmental, social, and future aspects.

The circular transition for companies fundamentally hinges on innovation, with a particular emphasis on product innovation (Chirumalla et al., 2024; Skare et al., 2024). This article posits that circular product development is the critical pathway for many companies embarking on their journey towards a CE. Existing academic work robustly supports this approach (Chiaroni et al., 2022). However, this aspect faces significant barriers that must be addressed. Indeed, the literature has extensively explored the multitude of barriers to the implementation of a CE, categorizing these challenges into three primary verticals: contextual barriers, economic barriers, and technical barriers (García-Quevedo et al., 2020; Truant et al., 2024). One potential avenue for overcoming these barriers is through the adoption of open

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innovation (OI) practices, which can facilitate knowledge exchange and collaboration among diverse stakeholders (Jesus & Jugend, 2021; Sgambaro, Chiaroni, & Urbinati, 2024). The intersection between OI and CE lacks an in-depth exploration, creating a knowledge gap (Bigliardi & Filippelli, 2021). Bridging this gap through theoretical studies and empirical research is essential to develop effective strategies and practices for circular product development (Bocken et al., 2023).

This research addresses the CE and OI gap by exploring how companies leverage OI for developing circular products (Ai et al., 2024). As such, the objective of this study is to analyse how specific OI practices can support companies in overcoming well-documented barriers to CE implementation while developing circular products (Jesus, Jugend, de Camargo Fiorini, & de Sousa Mendes, 2024). This analysis provides valuable insights into how these practices foster innovation facilitating the transition to circular production. The study also emphasizes the importance of context, exploring how the effectiveness of these practices varies between highly industrialized regions and less developed areas, highlighting the need for tailored strategies in different socio-economic settings (Martínez-Moreno et al., 2024). Accordingly, this study aims to answer the following overarching research question: *How do companies exploit Open innovation practices to overcome Circular Economy barriers while developing Circular Products?* To address this question, the study pursues three main research goals: (i) to identify the primary barriers faced by companies during the development of new circular products; (ii) to scrutinize the best suited OI practices to overcoming these barriers within the context of the CE; and (iii) to understand how companies in highly industrialized and less industrialized contexts differ and share commonalities in their exploitation of OI practices to address CE barriers while developing circular products.

This study uses multiple case studies (Yin, 2009), to analyse two companies from highly industrialized regions and two from less developed regions, addressing a literature gap (França et al., 2022; Suchek et al., 2021). Drawing from diverse sources, this study not only identifies the primary challenges that companies face in the transition to a CE but also highlights the effective OI practices they employ. In addition, it offers insights into CE-OI intersection for sustainability stakeholders, an underexplored area (Bigliardi & Filippelli, 2021; Sgambaro, Chiaroni, & Urbinati, 2024; Urbinati, Shams Esfandabadi, & Messeni Petruzzelli, 2023).This research contributes to the academic discourse by providing a nuanced understanding of how different regional contexts influence the implementation of CE and OI practices. Furthermore, it enhances the body of knowledge by detailing the specific mechanisms through which OI practices can mitigate the barriers to circular product development. By doing so, it proposes a comprehensive framework that can guide future research and practice in the field.

The study intends to make several theoretical contributions by expanding the understanding of the relationship between CE and OI. It shows how OI practices, such as collaborative networks and knowledge sharing, can effectively address the multifaceted barriers to CE implementation. This research also highlights the importance of regional context in shaping the implementation of CE, suggesting that tailored strategies are necessary for different economic and developmental settings.

For managers, this study offers practical insights into leveraging OI to overcome the barriers associated with transitioning to a CE. Managers can use the identified OI practices to foster a culture of collaboration and knowledge exchange within their organizations. For instance, by engaging with external partners, such as research institutions and industry consortia, companies can access new technologies and expertise that facilitate circular product development. Additionally, the study's findings on the economic and technical benefits of OI can help managers justify investments in these practices to stakeholders, thereby securing the necessary resources for CE initiatives.

Policymakers can use the results of this study to design supportive frameworks that encourage the adoption of the OI approach towards the implementation of CE and circular product development. By understanding the specific barriers that companies face, policymakers can develop targeted interventions, such as subsidies for circular innovations, tax incentives for sustainable practices, and regulations that promote collaboration across the value chain. Furthermore, the study highlights the need for region-specific policies that address the unique challenges of different economic contexts, ensuring that CE and OI strategies are effectively implemented across various sectors and regions.

Literature review

Circular economy and circular product development

CE, seen as a sustainable approach, contrasts with the linear model emphasizing extraction, production, use, and disposal (Franzò et al., 2021; Kirchherr et al., 2017). Kirchherr et al. (2017) define CE as an economic system replacing "end-of-life" with reduce, reuse, recycle, and recovery in production, distribution, and consumption.

CE operates at micro, meso, and macro levels (Khitous et al., 2020). The micro-level comprises companies, products, and consumers; the meso-level contains eco-industrial parks and industrial symbiosis (IS) networks, while the macro-level involves cities, regions, national, or global governments (Kirchherr et al., 2017). This study focuses on the micro level due to a lack of understanding about progressing towards CE (Baratsas et al., 2022; Kristensen & Mosgaard, 2019). This is crucial for both producers offering circular products and consumers who are informed about sustainability (Camilleri et al., 2023).

Business models are essential for CE implementation (Centobelli et al., 2020; García-Quevedo et al., 2020; Pieroni et al., 2019; Urbinati et al., 2020). However, this is increasingly integral to product design (Spreafico, 2022). Sustainable design focuses on creating eco-efficient products or services that enhance industry competitiveness and sustainable consumption (Mestre & Cooper, 2017). Early CE integration is vital, as changing resources, infrastructure, and activities post-commitment is challenging (Bocken et al., 2016). This paper adopts a product-centric CE approach, as product development serves as the entry point for many companies transitioning to CE. The focus on developing circular products allows companies to take incremental steps towards a comprehensive implementation of CE (Mestre & Cooper, 2017). By starting with product development, companies can gradually integrate CE principles into their operations, making the transition more manageable (Bocken et al., 2016). This approach not only facilitates the implementation of CE but also paves the way for systemic transformation in industry practices and supply chain dynamics.

However, this pathway is not exempt of obstacles. Several scholars have categorized CE barriers into distinct groups or verticals, offering a structured perspective on the challenges that organizations face during the transition (Kirchherr et al., 2018; Ritzén & Sandström, 2017; Van Eijk, 2015). These categorizations enable a clearer understanding of the nature and scope of barriers, facilitating targeted strategies to address them. Among the most commonly discussed verticals are Contextual, Economic, and Technical barriers, each representing unique challenges in the CE implementation journey (Kirchherr et al., 2018; Santolin et al., 2023).

Contextual barriers relate to the structural and cultural environment in which companies operate (Urbinati et al., 2021). This vertical includes challenges like complex supply chains, where production and consumption occur across multiple countries, requiring significant reorganization to support reuse and remanufacturing (Preston, 2012; Carissimi et al., 2024). Sustainability in these supply chains requires incentives to adopt sustainable materials, promote reparability, and ensure the existing network supports shifts in transportation modes. According to Kumar et al. (2019), another barrier is structural rigidity, where organizational hierarchies and managerial term restrictions stifle flexibility and innovation critical for CE adoption. Additionally, market and cultural resistance plays a role, as risk aversion, competition, and

reliance on traditional, resource-intensive models hinder progress toward more sustainable practices (Jaeger & Upadhyay, 2020). These contextual challenges underscore the need for systemic changes within and beyond individual organizations to create an enabling environment for CE.

The Economic barriers relate to the financial challenges associated with CE implementation (Kirchherr et al., 2018). Within this vertical, high start-up costs are a significant barrier, involving investments in retooling, relocating, building new infrastructure, and retraining staff, which can deter companies from committing to CE despite its long-term benefits (Salvador et al., 2022). Another economic challenge is business-to-business (B2B) cooperation, where the need for cross-company coordination leads to high transaction costs and delays, particularly in industrial symbiosis initiatives requiring detailed information exchange on material and energy flows (Van Eijk, 2015). The time-consuming and expensive nature of product disassembly is yet another hurdle, as existing designs often make it more economical to produce new products than to recover and reuse components (Franzò et al., 2021). Addressing these barriers requires innovative financing models, subsidies, and shared cost mechanisms to reduce the economic burden on individual companies.

Studies such as García-Quevedo et al. (2020) have pointed out a vertical characterized by technical barriers arising from the lack of skills, knowledge, and technology required for CE practices. A prominent barrier is the lack of information on product design and production, particularly regarding the removal of toxic materials, separation of biological and technical substances, and knowledge of green suppliers (Kirchherr et al., 2018). This knowledge gap hampers the development of CE-aligned products. Another critical issue is the lack of technical skills in small- and medium-sized enterprises, which often fail to recognize the benefits of adopting advanced technologies that enhance sustainability and cost efficiency (Dorrego et al., 2023; Rizos et al., 2016). Finally, quality compromise represents a significant barrier, as companies fear that prioritizing environmental considerations over performance could compromise product quality, leading to reluctance in adopting CE practices (Torstensson, 2016). Overcoming these technical barriers demands investments in education, training, and research to build capabilities aligned with CE objectives. The existing literature has claimed that the technical barriers, which include technological constrains, are among the most relevant challenges faced by companies transitioning towards the CE. The results and their consequent discussion will address this proposition. Table 1 summarizes the barriers used in this research.

Table 1
Circular economy barriers.

Vertical	Barriers	Definition	References
Contextual	Complex supply chains	Because production and consumption often take place in different countries, supply chains may need to be reorganised to facilitate reuse and remanufacturing. Incentives throughout the supply chain are needed for companies to actively consider sustainable materials, durability and reparability. For the CE transition, the existing network should support switching between transportation modes	Preston (2012), Van Eijk (2015), Urbinati et al. (2021)
	Structural	Innovation and flexibility are restricted by organisations' hierarchical patterns. CE's strategies are affected by the managers' employment term restrictions	Liu and Bai (2014), Jaeger and Upadhyay (2020), Kumar et al. (2019)
	Markets & culture	Competition in the marketplace restricts the movement towards CE. Managers are risk averse. Traditional models are highly resource-intensive; less resource intensive models are lacking.	Liu and Bai (2014), Jaeger and Upadhyay (2020)
Economic	High start-up costs	In the long run, the CE model would show sustainable benefits and increased growth. But, in the short run, the start-up costs are high involving, e.g. retooling machines, relocating factories, building new distribution and logistics arrangements and retraining staff. Lack of budget towards the CE model innovation. Lack of industrial symbiosis is a barrier towards CE because it is costly. Quality assurance for recycled material to be handled in a good manner is costly	Preston (2012), Liu and Bai (2014), Van Eijk (2015), Torstensson (2016), Jaeger and Upadhyay (2020), Urbinati et al. (2021)
	Challenging business-to-business (B2B) cooperation	A barrier is coordination across companies because it needs multiple companies to adjust their daily operations. This potentially gives large transaction costs and delays in negotiating among companies. Industrial symbiosis requires information exchange to get knowledge of	Van Eijk (2015), Jaeger and Upadhyay (2020)

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Open innovation and open innovation practices

Kristensen and Mosgaard (2019) argue that CE faces limited implementation due to the need for systemic innovation. To overcome barriers in CE implementation, Jesus & Jugend, 2021 recommend expanding organizational boundaries, collaborating with external parties, and accelerating innovation commercialization through shared knowledge and complementary resources.

Several studies propose strengthening collaboration with value chain stakeholders like suppliers, clients, and partners to harness external knowledge, technologies, and resources for new product and process development (Ambos et al., 2021; Lazzarotti & Manzini, 2009; Manzini et al., 2017). Similarly, CE-focused innovation necessitates knowledge and idea exchange with various entities, including other companies, suppliers, and clients (Brown et al., 2020; Dorrego et al., 2024; Lazzarotti et al., 2017).

Chesbrough (2017) acknowledges the rapid development of OI but emphasizes the need for a practical understanding of the concept amid confusion and distortion. Traditionally, two OI knowledge flows exist: inbound (outside-in) and outbound (inside-out) processes (Chesbrough, 2017; Lazzarotti et al., 2017). Some studies highlight a third coupled process in OI, where firms merge external knowledge acquisition with

Table 1 (*continued*)

Vertical	Barriers	Definition	References
		material and energy flows, which is costly or difficult	
	Disassembly of products is time-consuming and expensive	A product is made of many different components that are attached in a way that their disassembly is hard and time consuming, and it seems much better to produce a new product than to recirculate the materials, and it would be very expensive to mould the components in a way they could be available to use again	Torstensson (2016), Franzò et al. (2021)
Technical	Lack of information on product design and production	Removing of toxic material and separation of biological from the technical substance is lacking. Shortage of information regarding green suppliers. Current product design is given less attention towards the end phase of products	Van Eijk (2015), García-Quevedo et al. (2020), Kumar et al. (2019), Franzò et al. (2021), Salvador et al. (2022)
	Lack of technical skills	A barrier towards the implementation of CE is the lack of skills in small- and medium-sized enterprises. They do not realise the benefit of implementing more advanced technologies that reduce the negative impacts on the environment and would give them costs savings	Rizos et al. (2015), García-Quevedo et al. (2020), Kumar et al. (2019), Ritzén and Sandström (2017), Jaeger and Upadhyay (2020)
	Quality compromise	Companies' reluctant attitude towards CE is their concern regarding the quality of materials. They fear materials would be chosen based on the environmental aspects instead of the quality of performance	Torstensson (2016), Jaeger and Upadhyay (2020), Franzò et al. (2021)

internal idea commercialization to jointly develop and market innovation (Bigliardi et al., 2021; Strazzullo, Mauriello, Corvello, Cricelli, & Grimaldi, 2025).

Inbound Practices focus on leveraging external knowledge to enhance internal innovation processes (Lazzarotti et al., 2017). There is a vast literature pointing out that inbound OI practices are the most preferable actions for companies opening their innovation processes (Ardito et al., 2020; Sisodiya et al., 2013). Among the inbound OI practice tested, consumer and customer co-creation involves directly engaging consumers or customers in generating, evaluating, and testing new ideas, thereby ensuring that innovations align with market needs (Lazzarotti & Manzini, 2009). Although previous works have highlighted the relevance of this practice, our results would discuss this proposition and its applicability for two different contexts. Information networking entails informal knowledge exchange at events or conferences without contractual obligations, offering access to a diverse pool of insights (Spithoven et al., 2013). Another key practice is university-research collaboration, where companies fund academic research projects to access cutting-edge scientific expertise (Chesbrough & Brunswicker, 2014). Studies have also pointed out that Publicly funded R&D consortia facilitate collaboration with other organizations through partially or fully government-funded initiatives, supporting shared innovation efforts (Chesbrough, 2017; Chesbrough & Brunswicker, 2014). Therefore, from the relevant literature it is claimed that both, government support and collaboration with research institutions is vital in moving forward towards CE implementation. Similarly, contracting with external R&D service providers enables firms to access specialized services like technology scouting and virtual prototyping (Ebersberger et al., 2012).

According to Ambos et al. (2021), other inbound practices include idea and start-up cooperation, where companies invite entrepreneurial teams to submit innovative business ideas, fostering collaboration and venture support. IP in-licensing allows firms to acquire external intellectual property, such as patents or trademarks, via formal agreements. Supplier innovation sharing encourages existing suppliers to contribute innovative ideas, while crowdsourcing leverages external networks to solve problems through open calls for ideas. Lastly, firms may engage specialized services from OI intermediaries, which act as brokers between organizations seeking solutions and external networks capable of providing them (Chesbrough & Brunswicker, 2014; Ebersberger et al., 2012).

In contrast, Outbound Practices involve sharing or monetizing internal knowledge externally (Lazzarotti & Manzini, 2009). Chesbrough & Brunswicker (2014) point out a series of relevant practices such as joint venture activities with external partners that enable strategic and financial collaboration in independent ventures, or companies also engaging in the selling of market-ready products, transferring developed ideas to third parties for commercialization. Participation in public standardization activities helps shape industry standards through agencies like ISO. Corporate business incubation and venturing allows firms to develop and support entrepreneurial initiatives internally, exploring novel market opportunities (Lazzarotti & Manzini, 2009).

Other outbound practices include IP out-licensing and patent selling, where organizations monetize their intellectual property through licensing agreements or outright sales. Donations to commons or non-profits support open-source communities or external R&D by sharing internal knowledge or resources. Lastly, spinoffs represent investments in ventures founded by a company's employees outside its organizational boundaries, fostering innovation ecosystems (Chesbrough & Brunswicker, 2014).

By categorizing OI practices into these types, scholars provide a nuanced understanding of how firms can strategically manage knowledge flows to address specific barriers, including those encountered in CE initiatives. This classification highlights the diverse tools available to companies aiming to innovate collaboratively and overcome challenges in transitioning to sustainable models.

This study's product-focused approach aligns with integrating practices across diverse companies (Chesbrough & Brunswicker, 2014; Ramaswamy & Gouillart, 2010). Table 2 summarizes the OI practices used in this research from both inbound and outbound perspectives. In sum, this study aims to address the gaps in identifying which OI practices can serve as moderators in overcoming barriers to CE implementation.

Methodology

As depicted in Fig. 1, this study employs a three-stage structure to address the main research objective of the study; each stage is guided by a specific research question, each one encapsulated within the overarching question provided in the Introduction. Initially, it explores primary barriers faced by firms in creating circular products. Subsequently, it assesses the OI practices for addressing these hurdles. Finally, it compares companies in highly industrialized and less developed regions

Table 2
Open innovation practices.

Inbound practices		
Consumer and customer co-creation	Involvement of consumers or customers in the generation, evaluation, and testing of novel ideas for products, services, processes, or even business models	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012), Lazzarotti and Manzini (2009)
Information networking	Networking with other organizations without a formal contractual relationship, e.g., at conferences or events, to access external knowledge	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013), Lazzarotti and Manzini (2009)
University research collaboration	Funding of external research projects by researchers and scientists in universities (faculty, PhD students, or postdoctoral fellows) to access external knowledge	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013)
Publicly funded R&D consortia	Participation in R&D consortia with other public or private organizations in which R&D activities are fully or partly funded by governmental organizations (e.g., European Commission or National Science Foundation)	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012)
Contracting with external R&D service providers	Contracting with external service providers for specialized R&D services, including technology scouting, virtual prototyping, etc.	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012)
Idea and start-up cooperation	Invitation to entrepreneurial teams and start-ups to submit business ideas via open competitive calls, with collaboration and venture support to winning teams	Chesbrough & Brunswicker (2013, 2014), Ambos et al. (2021)
IP in-licensing	Licensing of external intellectual property rights (e.g., trademarks, patents, etc.) via formal licensing agreements	Chesbrough & Brunswicker (2013, 2014), Ambos et al. (2021)
Supplier innovation sharing	Invitation of existing suppliers to participate in innovation and submit innovative ideas	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013), Lazzarotti et al., 2017
Crowdsourcing	Outsourcing innovation problem solving (including scientific problems) via an open call to external organizations and individuals to submit ideas	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013), Ambos et al. (2021), Christensen & Karlsson, (2019)
Specialized services from OI intermediaries	Contracting services of intermediary organizations specialized in OI to act as intermediary between a "searcher"—an organization with an OI problem—and "solvers"—a network of organizations or individuals with potential solutions	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012)
Outbound practices	**Columna2**	**Columna3**
Joint venture activities with external partners	Strategic and financial investment in independent joint ventures jointly with external partners	Chesbrough & Brunswicker (2013, 2014), Ambos et al. (2021), Lazzarotti and Manzini (2009)
Selling of market-ready products	Sale of a market-ready novel product idea to a third party for sale to its customers	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013)
Participation in public standardization	Participation in standardization activities via formal standardization agencies (e.g., ISO) or informal standardization consortia (e.g., OASIS)	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013), Ambos et al. (2021)
Corporate business incubation and venturing	Corporate incubators or accelerators developing potentially profitable ideas and offering supportive environments for entrepreneurs inside the organization to identify novel paths to market	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012), Lazzarotti and Manzini (2009)
IP out-licensing and patent selling	Licensing of internal IP to external organizations via licensing agreements or selling via single payment	Chesbrough & Brunswicker (2013, 2014), Lazzarotti and Manzini (2009)
Donations to commons or nonprofits	Donations to commons or nonprofits (e.g., open-source communities) to support external R&D	Chesbrough & Brunswicker (2013, 2014), Spithoven et al. (2013)
Spinoffs	Investment in new ventures founded by firm's employees outside organizational boundaries	Chesbrough & Brunswicker (2013, 2014), Ebersberger et al. (2012)

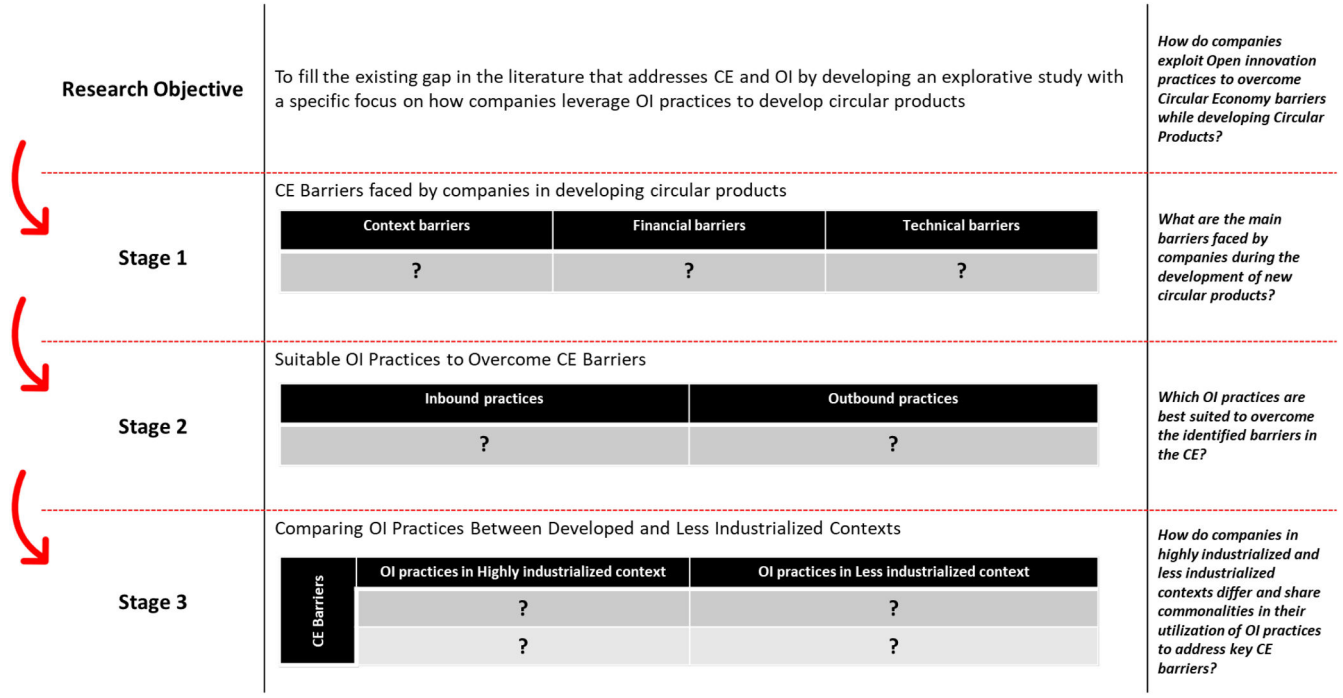

Fig. 1. Research structure.

regarding their use of OI practices to surmount critical CE barriers while developing circular products.

Multiple case study approach & comparative analysis

Recently, scholars have called for enhanced relevance and rigor in empirical research (Boyer et al., 2009; Eisenhardt & Graebner, 2007; Fisher, 2007). In addition, Organizational Management researchers have advocated for qualitative case study research (Lewis, 1998; McCutcheon & Meredith, 1993). Qualitative case studies utilize contextually rich data from specific real-world settings to investigate focused phenomena (Benbasat et al., 1987; Bonoma, 1985; Meredith, 1998; Yin, 2009). Literature suggests that multiple case research typically involves four to ten cases (Gustafsson, 2017; Yin, 2009); this study follows suit with four cases.

To justify theory-building from case studies, researchers must articulate their rationale (Eisenhardt & Graebner, 2007). Justifications include addressing gaps in existing theory (Benbasat et al., 1987; Eisenhardt & Graebner, 2007; Meredith, 1998), exploring and explaining phenomena (Benbasat et al., 1987; Bonoma, 1985), particularly the experiences of managers to enhance practical relevance (Fisher, 2007). Clear focus and systematic data collection are imperative for theory-building from case studies (Mintzberg, 1979). Defining the unit of analysis is crucial (Dubé & Paré, 2003; Yin, 2009a) as it helps identify relevant literature and set boundaries (Markus, 1989). Data sources include structured or semi-structured interviews, observations, and archival materials (Benbasat et al., 1987; Boyer & McDermott, 1999). Data analysis must occur incrementally with data collection (Glaser & Strauss, 1999; Urbinati et al., 2020). Case study limitations continue to be discussed, but the method gains popularity (Gustafsson, 2017; Urbinati et al., 2020).

Considering CE implementation via OI practices, disparities between companies in industrialized and less developed regions are significant. While firms in highly industrialized regions benefit from resources, infrastructure, and a mature innovation ecosystem (Manrique & Martí-Ballester, 2017; Zhu et al., 2006), companies located in less developed regions face distinct resource constraints and cultural contexts (Hall, 2012; Narula & Santangelo, 2008). Despite these challenges, both industrialized and less developed companies make progress in CE and OI (Abad-Segura et al., 2021; Alejandrino et al., 2021). A comparative analysis between them offers insights into CE and OI challenges and opportunities (Abad-Segura et al., 2021; Ferronato et al., 2019; Patwa et al., 2021; Suchek et al., 2021). Italy and Uruguay were chosen as the focus countries for this study for several reasons. Firstly, both countries have a diverse economy that includes a range of industries, making them suitable for comparative analysis (Collazzo & Taieb, 2015; Zheng et al., 2019). Secondly, both countries have a growing interest in the CE implementation and have adopted policies and initiatives to promote sustainable production and consumption (França et al., 2022; Schröder et al., 2020; Urbinati et al., 2021). Finally, both countries have a strong culture of innovation, making them ideal for studying the role of OI in the CE (Aboal et al., 2018; Lazzarotti et al., 2010; Schröder et al., 2020).

Data collection & processing

Data collection for the empirical research spanned from June 2022 to April 2023, primarily relying on in-depth interviews with key personnel related to the implementation of CE, including CEOs, CFOs, managing directors, and technical staff from the companies studied. These interviews, averaging about 90 min each, were semi-structured, adhering to a set of standard questions but allowing for open-ended exploration of relevant topics. (See Annex 1 for more detailed information on the interview protocol applied). A key tool in these interviews was a list of CE barriers and OI practices derived from relevant literature (see the previous Tables 1 and 2). After transcribing the interviews and organizing the collected documents, the researchers employed Atlas.ti, qualitative analysis software, to categorize the cases according to their CE barriers (Friese, 2019).

The interviews conducted in this study followed a structured coding protocol designed to ensure a systematic and rigorous analysis of the qualitative data. Considering that the questions in the questionnaire were straightforward, Reflexive Thematic Analysis (RTA) was applied to analyse the data. RTA is an accessible and theoretically flexible interpretive approach to qualitative data analysis that facilitates the identification and interpretation of patterns or themes within a data set (Byrne, 2022). As demarcated by Braun and Clarke (2012), RTA is distinct from other forms of thematic analysis by its emphasis on flexibility and reflexivity. They differentiate between three principal approaches to thematic analysis: (i) coding reliability TA, which emphasizes consistency across coders; (ii) codebook approaches to TA, which use predefined frameworks; and (iii) reflexive approaches like RTA, which prioritize the researcher's active role in meaning-making (Braun & Clarke, 2019). This approach was particularly suitable for this study, as it aligned with its exploratory nature and the need to interpret nuanced insights into CE barriers and OI practices. The protocol began with a preliminary open coding phase, where transcripts were reviewed to identify recurring themes and patterns related to CE barriers and OI practices. These codes were then refined through axial coding, which focused on categorizing the identified themes into broader conceptual groups corresponding to the theoretical framework, such as technical, economic, and contextual barriers, and different types of OI practices. Finally, selective coding was used to integrate these categories into a coherent narrative that addressed the research objectives and guiding questions.

Furthermore, while the interviewees were asked to assign numerical values using a 7-point Likert scale to assess the relevance of different CE barriers and to rank these barriers in terms of importance, this numerical data was not used to frame the study as a mixed-methods research design. A distinction must be made here: there is extensive literature emphasizing that the use of numerical techniques within a qualitative study does not automatically categorize it as mixed-methods research (Bracio & Szarucki, 2020; Halcomb & Hickman, 2015). For a study to be considered mixed-methods, its entire research design must be explicitly structured around integrating both qualitative and quantitative methodologies cohesively (Halcomb & Hickman, 2015). In this study, the use of numerical information was supplementary, serving to calibrate and validate the qualitative interpretations rather than define a separate methodological approach (Maxwell, 2010). Consequently, the research design remains firmly exploratory and qualitative in nature, underscoring its commitment to an interpretative understanding of the investigated phenomena.

The case study approach comprised four phases. The first phase involved meetings with key representatives to gain an initial understanding of the companies and background information. The second phase consisted of semi-structured interviews with executive managers, often conducted through digital means, for detailed company descriptions. The third phase analyzed informational material, including publicly available marketing content, social media, web pages, and internal documents. The fourth phase entailed the examination and analysis of business models and new product development strategies.

Additionally, the authors drew on their extensive experience with the companies, involving public presentations, meetings, and on-site visits, which provided valuable pre-existing knowledge. Fig. 2 illustrates the research method and its associated steps.

The selected cases

The selection of the four cases is based on their common company profile, marked by three important elements. First, all four companies are technologically advanced, which suggests that they may have more resources and capabilities to implement OI practices. Second, the four of them are exports oriented, meaning that they operate in a highly

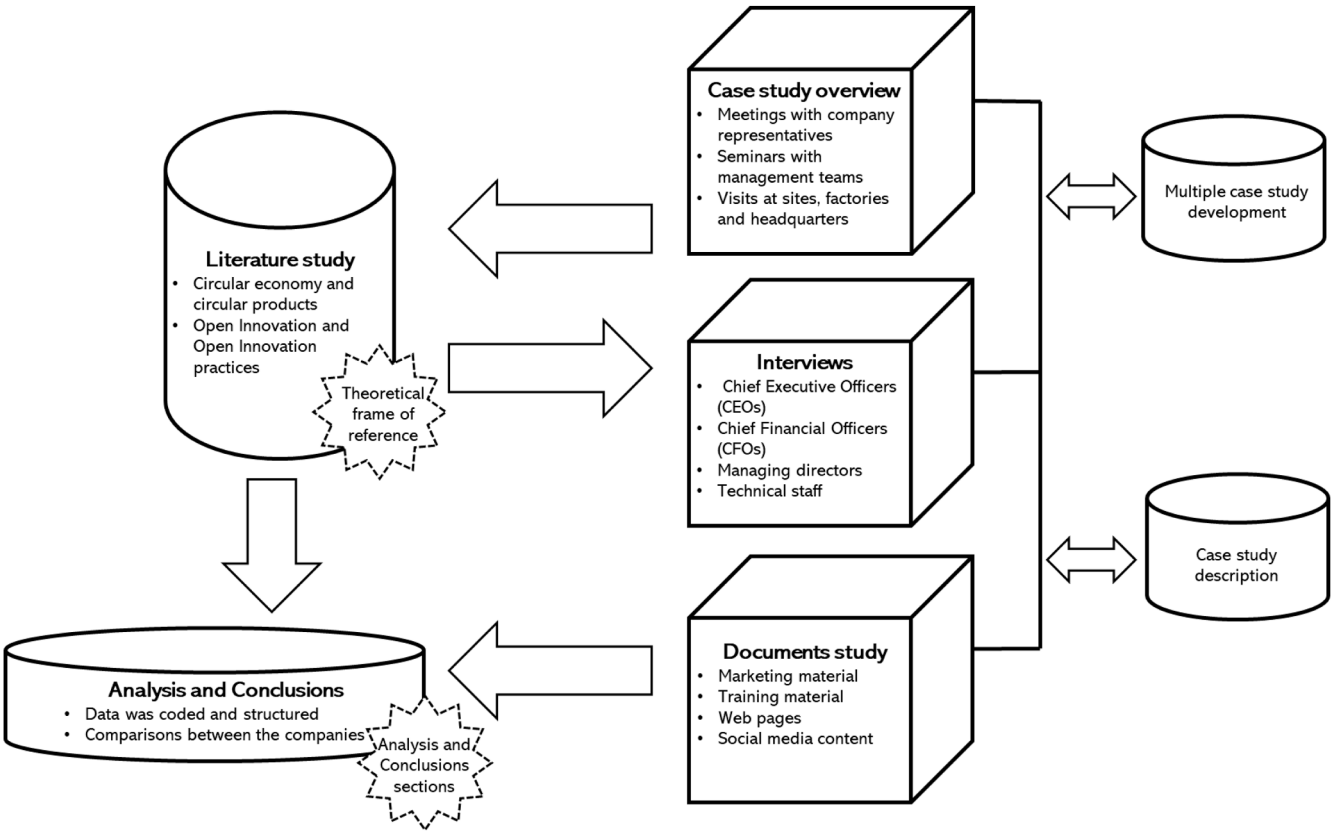

Fig. 2. Unfolding the research method.

competitive global market, where innovation can be a key differentiator for success. Third, all these companies claim to be sustainability-driven in their businesses, indicating a commitment to environmental responsibility and a focus on long-term value creation.

The common approach to business among these companies provides an opportunity for researchers to investigate how OI practices can be leveraged for the advancement of CE under different contexts. By comparing the experiences of these four companies, researchers can

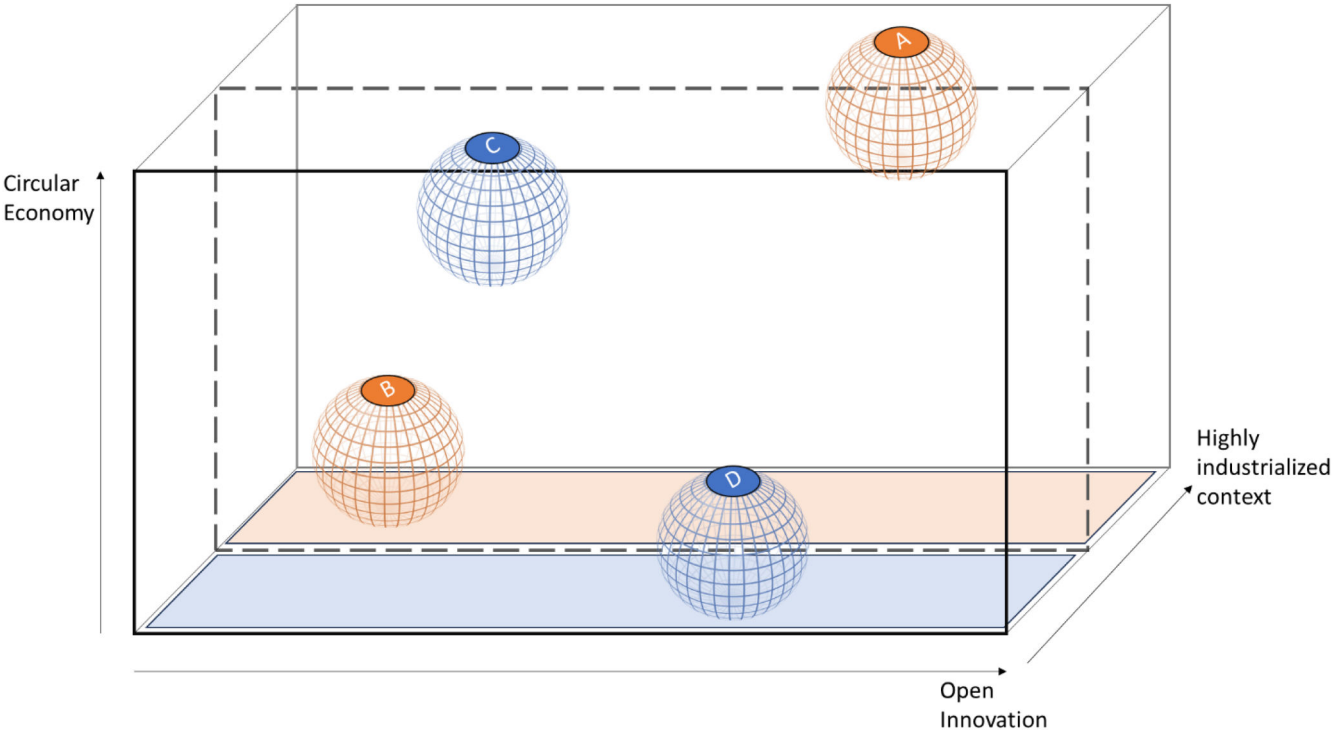

Fig. 3. Characterizing the cases of study.

identify best practices and strategies that can be applied to other organizations in different industries and regions.

Moreover, the focus on CE as a framework for sustainable development emphasizes the need for companies to adopt innovative and collaborative approaches to address environmental challenges. The incorporation of OI practices, which involves collaborating with external partners, can be a valuable tool in promoting CE and achieving sustainable development goals.

In summary, the choice of the four cases of study is grounded in their shared company profile as it is shown in Fig. 3. It provides a platform for comparative analysis of how companies exploit OI practices in the implementation of CE. The focus on CE as a framework for sustainable development highlights the importance of collaboration and innovation in addressing environmental challenges.

Company A

Company A, a leading European engineering thermoplastics manufacturer in Italy, provides 2500 customizable product formulations for global distribution across various industries like electronics, electrical, industrial, and transportation. With a €170 million annual turnover and 40,000-ton production capacity, it was founded in 1945, initially producing cellulose acetate compounds using Marshall Plan materials. Its founder's vision to "sort and recycle plastic from war remnants" has embedded CE principles as a core philosophy, a principle the current CEO considers integral to the company's DNA.

During the 80s and 90s, the company transitioned towards eco-sustainable products with energy-efficient processes. Today, it stands as one of Lombardy's prosperous family-run businesses, adhering to a Quality, Environment, and Health & Safety system. It actively minimizes its global environmental impact while fulfilling customer needs and sustainability objectives. The company prioritizes transparency and accountability to stakeholders, including employees, customers, and local communities. It achieves this through energy-saving measures, photovoltaic investments, and renewable energy procurement. Despite its energy-intensive operations, Company A remains dedicated to reducing consumption and environmental footprint.

Regarding innovation, Company A maintains an in-house R&D department dedicated to CE initiatives. However, most of its innovation processes involve external partners like suppliers, research centers, universities, corporate organizations, institutions, public agencies, and even competitors. Consequently, the firm's orientation heavily favours OI practices.

Company B

Company B, an Italian subsidiary of a global German multinational, specializes in rail and DC power safety and availability technologies. It infuses Italian craftsmanship, ergonomics, and style into its global operations. Established in Milan in 1947 as an Industrial Engineering Firm, it evolved under robust leadership during the late 80s to become a market leader in railway and industrial safety components.

Since 2015, it serves as the global Center of Competence for its German parent, enabling worldwide expansion and customized railway vehicle products in countries like the United States, China, South Korea, Russia, and beyond. This collaboration also extends to industry systems, new mobility, and renewable energy sources. In the Italian market, it offers the full product range and comprehensive pre-and post-sales support.

The production department, the company's core, adheres to rigorous quality, technical, technological, and safety standards. Supported by real-time input from engineering and 3D prototyping units, it employs cutting-edge digital technology. The company actively engages in cultural and educational initiatives for students, offering meetings, internships, work-study programs, and even its graduate program.

The CEO emphasizes that innovation must align with sustainability, and the company proudly adopts plastic-free practices. As part of their environmental commitment, treated and carbonated tap water is available via dispensers throughout the offices and production floors. While sustainability is integral to their activities, the CE is not a central aspect of their business model. The R&D laboratory has yet to address this issue, which both technical and managerial staff recognize as crucial for reaching new markets and customers.

In terms of innovation, Company B boasts a well-funded R&D unit that ensures innovation self-sufficiency. Despite multiple links and connections with other entities, the company predominantly focuses on internal innovation.

Company C

Company C transforms forest products into sustainable construction materials, aligning with CE principles to promote eco-conscious practices. Positioned as a circular bioeconomy leader, its mission is to advance timber solutions and sustainable building materials in Uruguay and beyond. The company envisions its sawmills as regional Mass Timber production models, aligning with the United Nations Sustainable Development Goals.

A subsidiary of a construction systems-focused business group, with Uruguayan and US investors, Company C made headlines in 2021 by acquiring an existing lumber company in Tacuarembó, Uruguay. This acquisition, hailed by Uruguay XXI, marked a pivotal moment in the industry, poised to double wood exports in the country. Subsequently, the firm embarked on two ventures: expanding timber production and establishing South America's largest Mass Timber plant. The facility revitalizes northern Uruguay, providing employment for over 250 individuals and representing a significant industrial investment for the region.

Mass Timber, a wood processing system, enables construction of tall buildings, residences, sports centers, medical facilities, schools, and other projects, catalysing environmentally sustainable housing construction. While it gained traction in 1990s Europe, Mass Timber has not fully blossomed in Latin America, despite environmentally friendly initiatives in transportation, food, and energy. The traditional construction sector, responsible for 40 % of greenhouse gas emissions (IEA, 2023), is now embracing sustainable solutions. Company C's CFO underscores Uruguay's competitive forestry resources and Mass Timber's potential to reduce CO_2 emissions by 2030, framing homes as future CO_2 repositories.

Innovation collaboration primarily involves technology integration and skill development with select suppliers. However, the company envisions robust partnerships with local and international stakeholders. A solid network connecting the company to research and training institutions is viewed as essential. While not fully realized, the orientation towards OI practices is evident.

Company D

In 1964, Company D initiated operations in Young, Río Negro, Uruguay, focusing on the metallurgical sector. The region boasts a thriving dairy basin, advanced agriculture, and a burgeoning forestry sector. Early days saw the company operate from a converted shed, blending living quarters with a workshop equipped with in-house manufacturing tools. It began crafting work tools for rural producers and, in the early 1970s, transitioned to mechanized bulk harvesting, replacing manual bag-based methods. Meeting the demand for harvest solutions, it diversified into producing grain elevators and harvesters' hoppers.

The pivotal year 1999, amid a severe regional economic crisis, found Company D with a diverse portfolio catering to agricultural production, encompassing vertical tillage equipment and forestry machinery. Market demand dwindled due to sectoral technological shifts, pausing its innovation pursuits. After a leadership generational shift and economic revival, the company recommenced innovation, specializing in agricultural-forestry machinery and manufacturing complementary components for globally sourced equipment. In 2006, it marked a turning point with its inaugural technology export, solidifying its status

as an agro-tech exporter. Collaborations with pioneering global technology companies have enriched its innovation landscape, offering access to novel technologies within a global value chain.

The CEO acknowledges Uruguay's competitive agricultural machinery market, driven by favourable import conditions, necessitating elevated quality and cost efficiency. Internationalization has manifested through expanded exports across Latin America and Africa. Company D thrives on co-creation, partnering with producers and engineers who comprehend their needs, fostering flexibility in technological enhancements, adaptations, and new research and development, characterizing it as an OI-oriented enterprise. In 2023, the company earned the National Academy of Engineering Award for an innovative project conducted with the Technological University (UTEC) and a multinational cellulose production company.

Sustainability and CE principles permeate the company's product development. However, achieving full circularity poses challenges, such as material capture intricacies during use and limited trust in recycled materials. Despite specific CE initiatives, the firm grapples with intricate technical aspects within this promising growth domain.

In sum, the studied companies are technologically advanced and export oriented. However, Companies A and B, in highly industrialized regions known for innovation, may differ in their path to sustainability and CE compared to Companies C and D, located in regions striving to catch up with innovation, placing greater emphasis on CE. The latter companies may face a comparative disadvantage in knowledge production and dissemination.

Companies A and C prioritize CE in production, especially at the product-design level, emphasizing their commitment to circular practices. In contrast, Companies B and D acknowledge circularity's importance but have limited circular product output, with only a few initiatives.

While Companies B and C are not deeply engaged in OI practices for innovation capacity, Company B, self-sufficient in innovation with a substantial R&D department, contrasts with Company C, which intends to collaborate with other stakeholders for innovative solutions.

Companies A and D demonstrate a clear orientation towards OI. Despite having internal R&D departments, they collaborate extensively with various stakeholders in innovation projects. They actively seek partners to acquire knowledge and skills, particularly for sustainable CE product development. The companies' location, circularity approach, innovation strategy, and use of OI practices distinguish them from one another. Fig. 3 shows a summary of the characteristics of the four cases involved in this research.

Results

Stage 1: barriers to circular economy

Addressing the primary research question, Table 3 summarizes data processing outcomes and key CE barriers for the four companies studied. In the "contextual" dimension, all companies identified "complex supply chains" as a CE barrier, reflecting the universal challenge of reorganizing logistics to facilitate reuse and remanufacturing. Companies A, B, and C ranked it third in importance, while Company D rated it slightly lower, placing it fifth. For Company A (thermoplastics in a highly industrialized region), the complexity arises from managing cross-border supply chains while ensuring compatibility with CE practices, such as using recyclable polymers. As the Manager of Logistics of company A would say, *"[…] the more sophisticated our products and production system has become, the more complex our supply chain has also developed"*. In contrast, Company C (engineered wood compounds in a less developed region) faces logistical difficulties due to limited infrastructure and fewer regional suppliers capable of meeting CE demands. These examples highlight how supply chain challenges manifest differently based on the industrialization level, yet consistently obstruct CE implementation.

The barrier of "innovation and flexibility constrained by

Table 3
Outcomes of the circular economy barriers' exploration.

	Barriers	Comments
Contextual	Complex supply chains	Companies have distinguished complex supply chains as a barrier to implementing CE practices. It seems that the challenge of reorganizing supply chains to facilitate reuse and remanufacturing is a common barrier for both highly industrialized and less developed regions.
	Structural	Companies have also identified structural barriers to implementing CE practices. However, they ranked it as a relatively low barrier. Company B may be the exception, which is the only one that accounts for a large R&D department. Hierarchical patterns, as well as managers' employment term restrictions, seem to restrict innovation and flexibility in adopting CE strategies.
	Markets & culture	Companies have recognized market and cultural barriers to implementing CE initiatives. The difference in scoring and rankings does not suggest a clear distinction between companies located in Europe and those functioning in less developed regions. Competition in the market, managers' risk-averse attitudes, and the lack of less resource-intensive models appear to be common barriers across different environments.
Economic	High start-up costs	Companies have also labelled high start-up costs as a barrier to implementing CE practices, although it seems to be more of a challenge for Companies B and D, which ranked it as a top barrier.
	Challenging business-to-business (B2B) cooperation	Companies have underlined the need for coordination across companies as one of the lowest barriers to implementing CE practices in relative terms. This coordination involves multiple companies adjusting their daily operations, which potentially results in large transaction costs and delays in negotiating among companies.
	Disassembly of products is time-consuming and expensive	Companies have categorized the disassembly of products as relatively low barrier to implementing CE practices. The exception of it may be company A which identified this barrier as the second most important. The time-consuming and expensive process of disassembling products makes it difficult to recirculate materials, which makes it more cost-effective to produce new products.
Technical	Lack of information on product design and production	While the lack of information on product design and production is one of the lowest barriers to implementing CE for companies located in the highly industrialized world, it seems to be very much relevant for those situated in less developed countries. Shortages of information regarding green suppliers, removing toxic material, and separation of biological from technical substances can be important challenges depending on where the business is developing.
	Lack of technical skills	Companies have identified the lack of technical skills as a top barrier to implementing CE practices. Although it is also relevant for company B, they

(*continued on next page*)

Table 3 (*continued*)

Barriers	Comments
Quality compromise	seem to mitigate its challenges by having a solid R&D internal unit. Companies have recognized the concern regarding the quality of materials as a barrier to implementing CE practices. Nevertheless, it seems to be more relevant for companies located in Europe and exposed to global markets to a greater level. Companies appear to be reluctant to adopt CE practices because they fear materials will be chosen based on environmental aspects rather than quality of performance.

organizational hierarchy" was generally less significant, except for Company B, which has a well-established R&D department. *"We believe that having a strong and well-funded R&D department is vital to be less dependent of other partners. However, it is also true that by internalizing our research capacity, we are investing a lot in addressing mid-managers' willingness."* (Company B's CEO). On the other hand, Company D (agro machinery) exhibits less hierarchical rigidity but lacks the institutional capacity for innovation, emphasizing how structural barriers disproportionately affect companies with established R&D units. *"Our flat organizational structure allows us to respond quickly to market demands, but without a well-funded R&D department, we often struggle to develop and implement innovative solutions aligned with circular economy principles. This limits our ability to compete with larger firms that have the resources to invest in long-term CE strategies"* (International Markets Manager, Company D).

Market competition and cultural resistance to change are pervasive barriers, irrespective of geographic or industrial context. For Company C, risk-averse management and a focus on traditional models hinder its ability to adopt less resource-intensive processes, like using locally sourced materials for engineered wood. Similarly, Company A grapples with competitive pressures to maintain cost efficiency, deterring them from investing in CE-aligned technologies. This underscores the need for broader cultural shifts and market incentives to promote resource-efficient models across diverse environments. As such, Companies A and C considered "marketplace competition hindering CE progress" moderately important, ranking it sixth and fourth, respectively. Companies B and D deemed it highly significant, placing it third. *"While we are fully convinced that sustainability in general, and CE, in particular, are the path to move on, it is true that the market is more focused in cost-reduction and the competition establishes an important barrier in progressing towards it"* (Company D's CEO).

Regarding the "economic" aspect, Companies A, C, and D saw "high start-up costs" as a CE barrier, with Company B rating it highly important and ranking it second. Therefore, the high costs associated with CE transitions, such as retooling or retraining, pose greater challenges for certain companies. For instance, Company B must invest significantly to transition its supply chain towards modularity and recyclability in train components, while Company D faces high capital expenditures in redesigning agricultural machinery to integrate recycled materials. Conversely, Company A's established supply chain and innovation-focused culture help mitigate this barrier, although costs remain a consideration. According to the CFO of Company C, *"embracing circularity requires significant investments in infrastructure, technology, and process redesign. While the long-term benefits are clear—reduced resource dependency, cost savings, and enhanced resilience—the initial financial outlay can be daunting. It's essential that we leverage strategic planning, innovative financing mechanisms, and collaborative partnerships to overcome this hurdle. By prioritizing smart investments and long-term value creation, we can unlock the full potential of the CE and drive sustainable growth for our company"*.

"Challenging business-to-business (B2B) cooperation" was less important for Companies A, B, and D but more so for Company C, ranking it eighth. Despite being ranked as a lower barrier, B2B coordination poses logistical and relational challenges. For example, Company C, operating in a less industrialized region, struggles to establish partnerships with green suppliers due to weak local networks. Conversely, Company A leverages strong industrial linkages in its region, using B2B relationships to co-develop CE-aligned materials. This illustrates how the perceived severity of this barrier depends heavily on regional ecosystem maturity.

Regarding the "Technical" dimension, Companies A, B, and C identified "lack of information on product design and production" as a barrier at the bottom of their lists, while Company D found it important, placing it fourth. *"For some of the products we produce, our customers, mostly industrial partners, are reticent about acquiring products that reuse materials due to safety concerns."* (Company D's CCO). This barrier is pronounced for Company D, located in a less developed region, where inadequate access to data on sustainable suppliers and recycling-friendly design practices limits progress. In contrast, Company A benefits from established design databases and supplier networks, enabling more informed CE decisions. This divergence highlights the informational disparity between highly industrialized and less developed regions.

"Lack of technical skills" was seen as a significant barrier by Companies A and B, ranking first and fourth, respectively. Companies C and D also considered it highly important, placing it at the top. This challenge seems particularly acute for companies operating in less developed regions, where access to specialized training and technical expertise is limited. According to the CEO of Company C, *"I firmly believe that the lack of technical skills poses a significant barrier in companies operating within less developed regions. To address sustainability challenges and fully embrace the principles of the CE, we must bridge the gap between industry needs and technical expertise. We urge governments, educational institutions, and relevant partners to collaborate closely with industries, bringing training programs and resources directly to where they are needed most. CE initiatives demand robust technical capacity, and by enhancing our workforce's skills, we can unlock untapped opportunities for progress and innovation. Let's seize the chance to accelerate our journey towards a more sustainable future."*

Echoing this sentiment, the Operations Manager of Company D emphasized, *"For us, technical skills are not just a nice-to-have but a critical factor in adopting CE practices. While our team has strong practical knowledge, the lack of advanced training in areas like material reuse and eco-design limits our ability to fully transition to circularity. We believe that partnerships with universities and technical institutes could provide the much-needed expertise to close this gap". These insights highlight how building technical capacity is essential for overcoming CE barriers and enabling companies to innovate effectively in both developed and developing contexts"*.

Commonalities among the companies included the recognition of "lack of technical skills" as a significant CE obstacle. *"As CEO, I see the lack of technical skills as an every-day barrier to achieving circular production in our industry, particularly in plastics manufacturing. Embracing circularity requires a deep understanding of materials science, innovative recycling techniques, and sustainable design principles. Overcoming this challenge demands a concerted effort to invest in upskilling our workforce, fostering collaboration with experts, and driving technological advancements. Only then can we truly revolutionize our approach to production, ensuring that every product we create contributes to a sustainable and regenerative future"* (Company A's CEO).

However, differences arose between highly industrialized and less industrialized regions. Companies in Uruguay were less concerned about material quality, whereas those in Europe, exposed to global markets, found it more relevant. As the CEO of company B would say *"[…] navigating the dynamic landscape of global markets, we recognize that material quality stands as a pivotal barrier on the path to achieving a CE, particularly in Europe. We believe that ensuring the integrity of materials throughout their lifecycle is paramount to unlocking the full potential of circularity. From sourcing to manufacturing to end-of-life processes, we must uphold rigorous standards for quality, innovation, and sustainability. By*

prioritizing material excellence, we can drive meaningful progress towards a CE, where resources are valued, reused, and regenerated for generations to come". Conversely, the importance of "lack of information on product design and production" varied, with Italian companies attributing less significance due to stringent regulations, while companies in less developed environments attached more importance to these issues. *"I see firsthand how the lack of comprehensive information on product design and production poses a significant barrier. Without clear insights into the materials and methods, we risk perpetuating a linear model of consumption and waste. Embracing the CE requires a fundamental shift in how we approach design and production, with transparency and collaboration at its core. By fostering a culture of knowledge sharing and innovation, we can break down these barriers and pave the way for a more sustainable future in construction"* (Production Manager of Company C).

The results reveal that while certain barriers are shared across contexts (e.g., complex supply chains and market resistance), others, such as technical skills and start-up costs, are more context-specific. The interplay between company characteristics (e.g., industry, size, and R&D capacity) and regional context (e.g., industrialization level) shapes how barriers are perceived and addressed. By recognizing these nuances, tailored strategies can be designed to mitigate specific barriers and advance CE implementation across diverse business and geographic landscapes.

Stage 2: open innovation practices to overcome the relevant circular economy barriers

Following the same procedure, interviews, and other materials were processed by applying a system of codes defined according to the OI's literature of reference. Consequently, the results are summarized in Table 4. This is an attempt to address the guiding research question for the second stage.

Consumer and customer co-creation is the primary inbound OI practice for Companies A and D, which are characterized as strongly OI-oriented. Company C, emphasizing "experiential customer satisfaction" in product design, also highly values this practice. It involves engaging consumers and customers in the innovation process to develop products aligning with their needs, enhancing satisfaction, and building loyalty. *"Experiential customer satisfaction is paramount for our company. We're committed to showcasing that our materials are not only safer, nicer, and potentially more cost-effective, but also environmentally friendly. Through immersive experiences, we aim to prove and convince our customers of these benefits, building trust and loyalty while driving sustainable growth"* (Sales Manager of company C). The integration of customer perspectives not

Table 4
Outcomes of the outbound open innovation practices exploration.

Inbound practices	Comments
Consumer and customer co-creation	This practice was highly relevant for Company A and Company D, with both companies assigning it the highest score. It was also important for Company B, with a score of 6. However, Company C assigned it a lower score of 5. Overall, it seems that involving consumers and customers in the innovation process is an important practice for companies implementing CE, particularly in highly industrialized environments.
Information networking	The results suggest that the importance of information networking may vary depending on the company and its environment. However, overall, this practice seems to be less important than other inbound OI practices for companies implementing CE.
University research collaboration	Companies A and B assigned relatively high scores to this practice, indicating that accessing external knowledge through funding of external research projects by researchers and scientists in universities is important. However, Companies C and D assigned lower scores, suggesting that this practice may be less relevant for companies in less developed environments.
Publicly funded R&D consortia	Companies A and D assigned relatively high scores to this practice, while Company B assigned the lowest score. Company C assigned a low score as well but ranked it higher than other practices. It seems that participating in R&D consortia with other public or private organizations in which R&D activities are fully or partly funded by governmental organizations may be a relevant practice for companies implementing CE, particularly in less developed environments.
Contracting with external R&D service providers	Companies assigned low score to this practice, suggesting that contracting with external service providers for specialized R&D services may be less important than other inbound OI practices for companies implementing CE. The exception could be company B which has been identified as less open-innovation oriented firm.
Idea and start-up cooperation	Company B assigned the highest score to this practice, while Companies A, C, and D assigned the lowest scores. This suggests that inviting entrepreneurial teams and start-ups to submit business ideas via open competitive calls, with collaboration and venture support to winning teams, may be more relevant for companies in highly industrialized contexts and denser R&D departments.
IP in-licensing	Companies A and B assigned relatively high scores to this practice, while Companies C and D assigned lower scores. It seems that licensing external intellectual property rights via formal licensing agreements may be a relevant practice for companies implementing CE, particularly in developed environments.
Supplier innovation awards	All four companies assigned the lowest scores to this practice, indicating that inviting existing suppliers to participate in innovation and submit innovative ideas may be less important than other inbound OI practices for companies implementing CE.
Crowdsourcing	Companies assigned relatively low scores to this practice, being company A the only exception. It seems that outsourcing innovation problem-solving via an open call to external organizations and individuals to submit ideas may be a relevant practice for companies implementing CE, particularly in developed environments without self-sufficient R&D units.
Specialized services from OI intermediaries	All four companies assigned low scores to this practice, suggesting that contracting services of intermediary organizations specialized in OI to act as intermediary between a "searcher"—an organization with an OI problem—and "solvers"—a network of organizations or individuals with potential solutions may be less important than other inbound OI practices for companies implementing CE.
Outbound practices	**Comments**
Joint venture activities with external partners	Company B scored the highest (6) on this practice, indicating that it is highly important for them. For the other companies it seems to be no relevant.
Selling of market-ready products	This practice does not seem to be a top priority for any of the companies, and there is no clear difference between the highly industrialized and the less developed environment.
Participation in public standardization	Companies B and A stated that this practice may not be relevant in their OI strategy focused in CE (both scored it 2). However, companies C and D scored it slighly higher (3), which may express that this practice seems to be more important for the companies located in a less developed regions (C and D) compared to the companies in a highly industrialized environment (A and B).
Corporate business incubation and venturing	This practice is shown to be significant for company B and company D. However, both companies A and C have not prioritized the incubation of business and venturing
IP out-licensing and patent selling	Company A scored it the highest (6). Also company D scored it moderately important (3). These are coincidently the companies more oriented to CE.
Donations to commons or nonprofits	None of these 4 companies have pointed out this practice as relevant in their strategy.
Spinoffs	Investment in new ventures founded by firm's employees outside organizational boundaries seems to have some relative relevance for companies A and B. It is not underlined as a relevant practice for companies C and D. There may be differences between companies in highly-industrialized area and those located in less developed countries.

only aligns with sustainable product goals but also strengthens the social license to operate, a crucial factor in CE transitions. As Company A's CEO elaborated: *"Customers are no longer just end-users; they are pivotal stakeholders. Their insights help us refine product circularity and ensure alignment with societal expectations, creating a mutually beneficial pathway toward sustainability"*. This reflects a broader trend in OI literature, where customer engagement drives not just innovation but also market acceptance of CE solutions.

The study underscores the importance of consumer and customer co-creation for companies adopting CE in product development. *"We firmly believe that customers play a pivotal role in driving innovation towards circular product development. We actively engage with our clients, recognizing their invaluable insights and ideas as catalysts for change. For example, we have a significant client who consistently challenges our designers to rethink existing products, pushing the boundaries of circularity. This collaborative approach not only strengthens our relationships with customers but also fuels our commitment to continuous improvement. By listening attentively to their needs and aspirations, we co-create solutions that not only meet but exceed expectations, paving the way towards a more sustainable future together"* (CEO of Company A). In contrast, supplier innovation awards, specialized services from OI intermediaries, crowdsourcing, selling market-ready products, and donations to commons or nonprofits received low ratings from all four companies.

Information networking's significance varies by company and context. In less industrialized settings, being well-connected may differentiate actors. Customizing OI practices to each company's unique needs—including size, industry, location, and innovation goals—is crucial. Assessing the benefits and costs of information networking is essential before implementation, although it appears less vital for CE-focused companies. The R&D responsible person in Company D pointed out that *"take, for instance, a small manufacturing firm in a rural area of a developing country. While they may lack access to sophisticated infrastructure or extensive industry networks, their close-knit community and relationships with local suppliers could provide unique advantages. By customizing their OI practices to leverage these local connections, they can tap into valuable resources, knowledge, and support systems. Assessing the benefits and costs of expanding their network beyond their immediate surroundings becomes crucial. However, for a company with a strong focus on CE principles, the emphasis might shift towards collaboration within the local ecosystem, where the benefits of shared knowledge and resources outweigh the costs of broader networking initiatives"*. This observation underscores the importance of leveraging context-specific advantages in less industrialized regions. As the sustainability officer from Company D emphasized: *"Our localized approach to networking has been a game-changer. It allows us to bypass systemic barriers often faced in under-resourced regions, creating a resilient innovation ecosystem that directly benefits our operations and communities*". However, these findings also suggest a potential trade-off; while local networks foster immediate operational synergies, they may limit exposure to global best practices in CE innovation, which is particularly relevant for scaling circular solutions.

Companies A and B, in industrialized contexts, highly value funding university research projects to access external knowledge. They collaborate with local universities and research centers, leveraging expertise for CE product development. Conversely, Companies C and D, from less developed regions, assign lower scores, indicating either limited access to or a lower prioritization of other OI practices. Access challenges persist in less industrialized regions. This difference highlights an inequity in the global innovation landscape. As the CEO of Company B noted: *"Our partnerships with universities have enabled us to drive forward not just CE innovations but also knowledge diffusion within our sector. This creates a competitive edge that would be unattainable without such collaborations"*. Conversely, limited access for Companies C and D reflects the structural challenges of aligning academic expertise with local industry needs in less developed regions. Bridging this gap requires targeted policy interventions to incentivize and facilitate such collaborations in regions where they are lacking.

Participating in R&D consortia is relevant for CE implementation, particularly in highly industrialized environments. *"At our company, we are deeply intertwined with our local and national ecosystems. Our commitment extends beyond our immediate operations to foster strong relationships with public actors and agencies. Collaboration in R&D initiatives, alongside policymakers and other public institutions, is not just an occasional endeavour—it's ingrained in our organizational ethos. By actively engaging in these partnerships, we not only contribute to the advancement of innovative solutions but also ensure that our actions align with broader societal goals and needs. It's an integral part of who we are and what we do, driving progress and creating lasting impact within our communities"* (Company A's CEO). Companies A and D, classified as OI-oriented, rate this practice highly, while Company B ranks it lower. Company C acknowledges some importance. Relevance hinges on the company's context and access to government funding and collaborations, favouring those situated in highly industrialized regions. The strategic role of R&D consortia is further illuminated when viewed through the lens of systemic transitions. As the Sustainability Officer of Company D remarked: *"Consortia are not just about shared knowledge; they are about shared responsibility. The challenges of CE demand collective action, and by pooling resources, we accelerate innovation while spreading risks across multiple stakeholders"*. These partnerships can serve as catalysts for addressing large-scale CE challenges, such as infrastructure redesign and material circularity. However, the findings also reveal uneven participation, emphasizing the need for equitable access to these consortia across regions and industries

Contracting specialized R&D services scores relatively low among companies implementing CE, except Company B. This preference for in-house R&D reflects the company's strong internal innovation capacity and a broader trend in industrialized settings, where firms with mature R&D units often deprioritize external collaboration. While this approach enables streamlined decision-making, it may limit exposure to disruptive ideas often fostered by external partners, such as startups or academia. As such, the R&D Manager of company B stated, *"Thanks to our robust R&D department, we possess the expertise and resources to tackle complex challenges internally. When it comes to projects related to circular production, we prioritize maintaining full control over the process and outcomes. While collaborations with external consultants and experts can bring valuable insights, we often find that keeping the project entirely in-house allows us to leverage our existing knowledge and capabilities more effectively. This approach not only ensures seamless alignment with our company's objectives but also enables us to innovate with agility and precision, driving impactful results in the realm of CE initiatives"*. For some, like Company B, it may be more relevant. However, most favour other inbound OI practices for CE success.

Company B values the relationship with entrepreneurial teams and start-ups, suggesting it is suitable for highly industrialized contexts with robust R&D. Collaboration and venture support play a vital role. *"At our company, we have a passion for nurturing innovation, especially when it comes to sustainability. That's why we actively seek out and support start-ups and young entrepreneurs with promising, sustainable ideas. We believe that these budding innovators hold the key to unlocking new pathways to circularity. By providing resources, mentorship, and opportunities for collaboration, we empower these visionaries to bring their ideas to life and drive meaningful change in our industry. Supporting start-ups isn't just about fostering entrepreneurship—it's about fostering a culture of innovation that propels us towards a more sustainable future" (R&D Manager of Company B)*. This strategy not only positions Company B as an active contributor to the broader innovation ecosystem but also reinforces its reputation as a sustainability leader. By aligning their goals with entrepreneurial agility, they mitigate risks often associated with rigid internal R&D frameworks. This approach, however, may not apply to companies with less developed R&D or industries characterized by lower innovation intensity, where resource constraints or a lack of local entrepreneurial ecosystems may limit similar ventures. This may not apply to companies with less developed R&D or less innovative industries.

Licensing external intellectual property rights through formal

agreements is relevant for CE implementation, especially in highly industrialized environments, as seen in Companies A and B's high scores. This practice allows these firms to expedite innovation while circumventing the resource-intensive development of technologies internally. As the CEO of Company A observed, *"IP licensing allows us to leapfrog technological hurdles, enabling rapid prototyping and deployment of circular solutions. It's an essential mechanism for scaling innovations that align with our sustainability goals without reinventing the wheel."* Conversely, Companies C and D assign lower priorities to this practice, likely due to cost barriers or limited access to licensable CE technologies. Companies C and D prioritize differently, possibly due to other challenges or barriers. Inviting existing suppliers to participate in innovation and submit ideas scores lowest among inbound OI practices for CE. This reflects the inherent challenges of transitioning traditional supply chains to support circularity. Suppliers rooted in linear models may lack the ability or incentive to innovate collaboratively. Instead, many companies favour new external partners who can better align with their circular objectives.

Outsourcing innovation problem-solving through open calls garners relevance, especially in highly industrialized contexts lacking self-sufficient R&D units, with low scores from all but Company A. Intermediary organizations specialized in OI also receive low scores, indicating a preference for direct connections with external stakeholders among CE-focused companies. This finding underscores a critical aspect of CE innovation: trust and control. Direct partnerships with stakeholders ensure alignment on goals and facilitate the nuanced exchange of knowledge required for circularity. As one innovation manager from Company D remarked, *"While intermediaries can provide structure, they often dilute the immediacy of collaboration needed for effective CE innovation."*

The findings reveal a clear preference for inbound practices over outbound practices. Most outbound OI approaches received lower ratings and were rarely highly regarded by the companies studied. This indicates that these companies were more inclined to engage in collaborative efforts with external partners to acquire new knowledge, technologies, and skills, rather than licensing or selling their internal intellectual property or products to external parties. Inbound practices were favoured because they facilitated the acquisition of novel knowledge and skills that the companies lacked, while outbound practices were less effective in creating value. This emphasis on inbound practices aligns with the resource-constrained reality of CE transitions. Firms prioritize acquiring what they lack—be it expertise, technologies, or market insights—over leveraging what they already possess, as these are often insufficient to address CE barriers.

Among the outbound OI practices examined, joint venture activities with external partners were crucial for Company B, ranking first with a score of 6. This finding highlights the strategic importance of deep partnerships for fostering shared accountability in innovation. As Company B's CEO put it, *"Joint ventures are a way to pool risks and resources, especially when tackling ambitious CE initiatives. By aligning incentives with our partners, we ensure that circularity becomes a shared goal, not just a corporate aspiration."* Conversely, Companies A, C, and D assigned lower scores and rankings for this practice, with Company A placing it fourth in importance. Selling market-ready products, another outbound practice, was deemed irrelevant for these companies. Participation in public standardization was relatively important for companies in less developed regions, as evidenced by higher scores and rankings for Companies C and D. This suggests the significance of government support and the impact of public policies in advancing the CE in the less developed regions.

Corporate business incubation and venturing yielded mixed results. It appeared relevant for Company B, closely aligned with innovation, and interested in promoting joint ventures with promising business partners. It was also relatively significant for Company D, despite operating in a different context but sharing an industrial focus on heavy machinery. However, it did not hold importance for Companies A and C, which were more advanced in circular production. In contrast, IP out-licensing and patent selling were significant for Company A, with a score of 6 and a top-ranking order. This practice was also relevant for Company D, suggesting that it is valued by those with a stronger OI orientation.

Donations to commons or nonprofits were not relevant for companies implementing CE. However, investments in new ventures initiated by the firm's employees beyond organizational boundaries garnered some attention from companies in advanced industrial contexts. This practice reflects an emerging recognition of the value of intrapreneurship in driving CE innovation. By empowering employees to experiment outside the formal organizational structure, companies tap into unconventional ideas and entrepreneurial energy. As noted by an R&D Manager at Company B, *"Encouraging our employees to venture beyond corporate boundaries has led to unexpected innovations that we later integrated into our core strategy"*. Both Companies A and B engaged in this OI practice, albeit not as a central strategy in their circular approach.

Regarding practices that differentiate companies in highly industrialized and those in less developed regions, university-research collaboration and investments in new ventures founded by the firm's employees outside the organization were found to be relevant in advanced industrial contexts. Regarding university research collaboration, the CEO of Company B claims, *"At our company, collaboration with universities isn't just an option—it's a fundamental pillar of our approach to innovation and sustainability. We've established robust educational programs in partnership with universities, where our employees undergo training to stay at the forefront of industry advancements. Moreover, we actively seek opportunities to apply for national funds alongside our academic partners, leveraging our combined expertise to drive impactful research and development initiatives. Beyond project-based collaborations, universities serve as a permanent point of consultation for us on sustainability matters, enriching our decision-making processes with their academic insights and expertise. Together, we're not just shaping the future of our industry—we're shaping a more sustainable world"*.

Participation in public standardization was more valued by Companies C and D, located in less developed regions, than by those firms in highly industrialized contexts, such as Companies A and B. This highlights the vital role of government support in establishing a foundation for CE practices. "*Yes, the government and policymakers undoubtedly play a pivotal role in championing the CE agenda. We stand ready to collaborate closely with them on this crucial mission. One area where their support is particularly vital is in promoting standardization and related practices. By establishing clear standards and frameworks, the government can provide the necessary guidance and incentives for businesses to embrace circularity fully. Through collaboration and shared goals, we can work hand in hand with policymakers to create a regulatory environment that fosters innovation, sustainability, and economic growth for all" (CFO of Company C)*. This insight points to an important dynamic: in less industrialized regions, standardization and public policy interventions compensate for weaker market-driven innovation mechanisms. Such policies also help level the playing field, enabling smaller firms to participate in the CE transition. Licensing external intellectual property rights through formal agreements was important for companies in highly industrialized environments.

Corporate business incubation and venturing held less importance, while IP out-licensing and patent selling were relevant for companies implementing CE. Companies more engaged in OI practices rated information networking and publicly funded R&D consortia highly. For instance, the CEO of Company A asserted, "*We must embrace innovation with open arms. Building a robust network for exchanging information is paramount for us. This entails staying vigilant about opportunities for collaboration, including accessing public funds for research and development or forming consortia with public agencies. These partnerships are catalysts for accelerating our journey towards circularity, enabling us to navigate challenges and seize opportunities with agility and purpose. By fostering a culture of openness and collaboration, we can drive meaningful progress"*. On the

contrary, idea and start-up cooperation and joint venture activities with external partners received high rankings only from companies less oriented towards OI.

Stage 3: commonalities and differences in tackling circular economy technical barriers by exploiting inbound open innovation practices

After examining the findings for stages 1 and 2 in the previous sections, it becomes evident that technical barriers are the most significant challenges companies encounter when transitioning towards circular production. Furthermore, the prevailing OI practices employed to overcome these barriers are inbound OI practices, notably publicly funded R&D consortia, consumer or customer co-creation, and university research collaboration. As a result, the subsequent discussion will center on this intersection, delving into how these technical barriers are being addressed through the mentioned inbound OI practices. Additionally, this section of the study highlights the similarities and differences between companies located in highly industrialized regions and those situated in less developed contexts. The analysis demonstrates that OI practices are not merely tools for problem-solving but also mechanisms for fostering systemic change, especially in aligning organizational strategies with CE implementation. Fig. 4 visually illustrates the logical flow of the examined phenomenon.

Addressing technical barriers with open innovation practices

CE initiatives have recently gained attention for their potential to address environmental issues and foster economic growth (Androniceanu et al., 2021; Chen et al., 2020; Ferrante & Germani, 2020). Yet, companies in industrially less developed regions, especially the Global South, may encounter unique CE implementation challenges compared to their highly industrialized counterparts like Europe (Ferronato et al., 2019; França et al., 2022). A key observation is that the ability to overcome technical barriers often hinges on the region's regulatory frameworks and access to resources. In highly industrialized regions, stringent regulations compel firms to adopt advanced OI practices to meet compliance and consumer expectations. Conversely, in less developed regions, companies leverage OI as a compensatory mechanism to address resource and capability gaps.

In advanced regions like Europe, material quality concerns underlie companies' hesitance toward CE, echoing recent research (Alonso-Almeida et al., 2021; Anastasiades et al., 2021; Skare et al., 2024). Europe tends to introduce standards from an economic rather than environmental perspective, affecting material preferences (Anastasiades et al., 2021). These concerns highlight a paradox: while CE principles advocate for reuse and recyclability, market resistance to secondary materials due to perceived quality and durability issues persists. This points to the need for enhanced collaboration between companies and consumers to reshape market expectations and standards. For instance, Company A's CEO notes, "*Clients resist high reused material percentages due to durability and technical adequacy concerns, reflecting cultural CE implementation battles within markets*".

Conversely, companies in less developed regions focus on addressing knowledge gaps in product design and manufacturing for CE. Stricter regulations in highly industrialized areas explain the difference (Gumley, 2014; Mizrachi & Tal, 2022; Triguero et al., 2013). Less developed regions often lack robust regulatory frameworks and strong institutional support, which impedes the transition to CE practices (Ferronato et al., 2019; García-Quevedo et al., 2020). Limited access to advanced technologies and materials exacerbates information shortages, making CE implementation harder (Franzò et al., 2021; Kumar et al., 2019). This study reveals that these gaps are often exacerbated by a lack of technological infrastructure and limited collaboration with knowledge institutions. OI practices, such as university collaborations and publicly funded R&D consortia, emerge as critical tools for bridging these gaps, enabling firms to access expertise and technological advancements that are otherwise unavailable internally. This study empirically highlights the differences between highly industrialized and less developed regions.

For companies in highly industrialized regions, such as Europe, the most salient technical barrier lies in addressing consumer resistance to materials with high percentages of recycled content. The results indicate that this resistance is closely tied to concerns over product durability and technical adequacy, compounded by entrenched cultural perceptions about the quality of reused materials. This suggests that inbound OI practices, particularly consumer co-creation, serve as a critical tool for bridging this perception gap. Through direct engagement with end-users, companies can tailor solutions that demonstrate the viability and performance of circular products, thereby building consumer trust and reducing market resistance.

In contrast, companies in less developed regions face barriers rooted

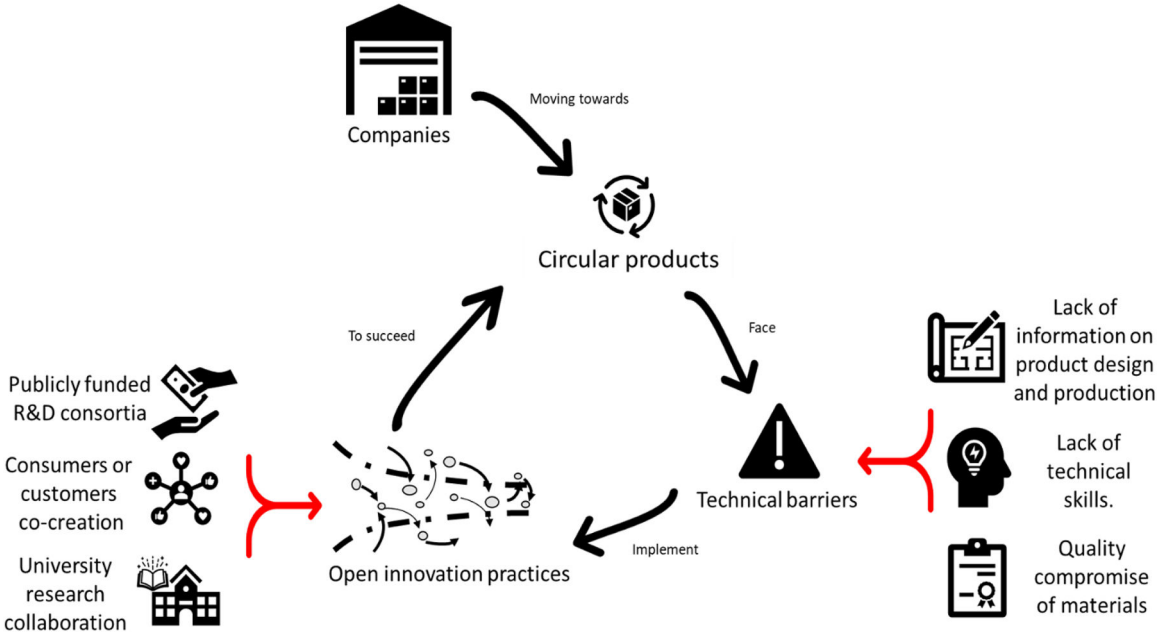

Fig. 4. Filling the research gap.

in foundational knowledge deficits, such as the lack of expertise in designing and manufacturing circular products. This finding underscores the importance of publicly funded R&D consortia and university collaborations in these contexts. By facilitating access to specialized knowledge and fostering collaborative environments, these OI practices enable firms to acquire the technical skills necessary for CE implementation, such as product design for disassembly and sustainable material sourcing. The study provides concrete evidence that these collaborations are not only vehicles for knowledge transfer but also catalysts for building localized innovation ecosystems that are better equipped to address regional CE challenges.

Technical skills and workforce development as cornerstones of CE transitions

Technical barriers are a common challenge for CE implementation (Brown et al., 2020; Chiu & Lin, 2022). In both highly industrialized and less developed contexts, lacking technical skills is a significant obstacle. Technical skills encompass specialized knowledge needed for CE practices, from sustainable materials to resource-efficient value chain management (García-Quevedo et al., 2020; Jaeger & Upadhyay, 2020; Ritzén & Sandström, 2017).

Limited access to education and training, a skilled labour shortage, and inadequate research funding contribute to skill deficiencies (Grafström & Aasma, 2021; Hopkinson et al., 2020; Jawahir & Bradley, 2016; Schipper & Silvius, 2021; Schröder et al., 2020). This dearth hinders CE practices and disrupts sustainability objectives. Inadequate technical skills may impede circular product optimization, material sourcing, disassembly, reprocessing, and the development of new circular business models. Thus, investing in workforce training, education programs, and external partnerships is crucial (Rauter et al., 2019).

Companies adopt alternative strategies to combat these challenges through OI practices. Inbound OI, sourcing external knowledge to solve internal issues, is preferred over outbound practices, which monetize internal ideas (Ardito et al., 2020; Schroll & Mild, 2011; Sisodiya et al., 2013). Inbound OI enhances innovation quality, reputation, collaboration, and cost-efficiency (Ardito et al., 2020; Sisodiya et al., 2013). It fosters a collaborative corporate culture, motivating employees and boosting productivity, creativity, and innovation (Cossío-Silva et al., 2016; Santolin et al., 2024). This approach is cost-effective and mitigates risks compared to in-house development (Schroll & Mild, 2011).

In sum, technical skill deficiencies emerge as a common barrier across both contexts. However, the study highlights a key distinction: while firms in highly industrialized regions face a shortage of highly specialized skills (e.g., in advanced material science and circular business model innovation), those in less developed regions struggle with more basic skill gaps, such as understanding CE implementation and applying existing technologies effectively. This divergence suggests that inbound OI practices must be adapted to the specific technical maturity of the region. For instance, in less developed areas, university collaborations that focus on basic training and capacity-building are critical, whereas in advanced regions, partnerships may prioritize cutting-edge research and technological co-development.

Consumer and customer co-creation as a driver for CE adoption

Co-creation with consumers and customers is deemed vital for CE, particularly by Companies A and D, recognized for their OI orientation. This emphasis is driven by stakeholder engagement and the need for sustainability alignment. Involving stakeholders generates valuable insights and builds trust, aligning with responsible consumer behaviour trends. For example, Company B leveraged co-creation to design products that aligned with customer durability requirements while maximizing recycled content. This practice not only mitigated technical barriers but also generated market insights that informed broader strategic decisions, such as material sourcing and product pricing. The findings suggest that co-creation is most impactful when companies actively integrate consumer feedback into the innovation process, creating a feedback loop that enhances both technical performance and market acceptance.

However, co-creation with consumers and customers presents challenges, including resource constraints and intellectual property (IP) concerns. Companies must balance benefits and risks, considering stakeholder engagement as part of CE initiatives. Collaborating with other stakeholders like suppliers or academic institutions complements consumer co-creation. As such, the study also identifies significant limitations associated with co-creation, particularly in resource-constrained environments. Companies in less developed regions reported difficulties in allocating resources to manage co-creation initiatives effectively, as well as concerns over intellectual property risks. These findings imply that for co-creation to succeed in such contexts, firms may require external support, such as public funding or access to shared innovation platforms, to offset these challenges.

University-industry collaboration: a double-edged sword

University-industry collaboration enhances CE in highly industrialized regions (Băban et al., 2022; Lam et al., 2013; Lazzarotti et al., 2017; Osorno-Hinojosa et al., 2022). For instance, Company A successfully partnered with a leading university to develop a novel recycling technology, reducing dependency on virgin materials and enabling the integration of higher percentages of recycled content into their products.

However, this synergy is less significant in less industrialized areas due to limited research capabilities, divergent priorities, SME resource constraints, and unfavourable policies. Boosting collaboration between industry and universities can overcome these barriers and promote CE practices in such regions. This finding highlights the need for targeted policy interventions to enhance the role of universities in CE transitions. For example, incentivizing universities to prioritize applied research in CE and fostering partnerships with international institutions could help bridge the capability gap in less developed regions. Moreover, creating multi-stakeholder consortia that include universities, industry players, and government agencies may provide a more integrated approach to addressing CE challenges.

Regional differences and systemic implications

The study underscores that regional disparities in technical barriers and the efficacy of OI practices are deeply rooted in structural factors, such as regulatory frameworks, market maturity, and institutional capacity. For companies in highly industrialized regions, regulatory stringency drives innovation, pushing firms to adopt advanced OI practices to meet compliance and market demands. In less developed regions, the absence of robust regulations and institutional support necessitates a more grassroots approach, with firms relying heavily on external partnerships to compensate for internal deficiencies. This divergence suggests that OI practices are not merely tools for overcoming barriers but also reflective of broader systemic dynamics that shape the trajectory of CE implementation in different contexts.

The findings of this study reveal that inbound OI practices are most effective when tailored to the specific barriers faced by companies, taking into account regional contexts and organizational capacities. More importantly, these practices enable firms to move beyond incremental problem-solving toward systemic transformation, fostering collaboration, knowledge-sharing, and the co-creation of value across entire value chains. Fig. 5 captures these dynamics, illustrating the pathways through which companies transition toward circular production by leveraging OI practices.

Theoretical contributions and implications

This study offers significant contributions to the evolving body of knowledge at the intersection between CE and OI. First, it deepens the understanding of the CE-OI relationship by elucidating how OI practices, such as stakeholder collaboration and knowledge sharing, can mitigate CE barriers, particularly those associated with circular product development. By focusing on OI practices like co-creation, open data usage,

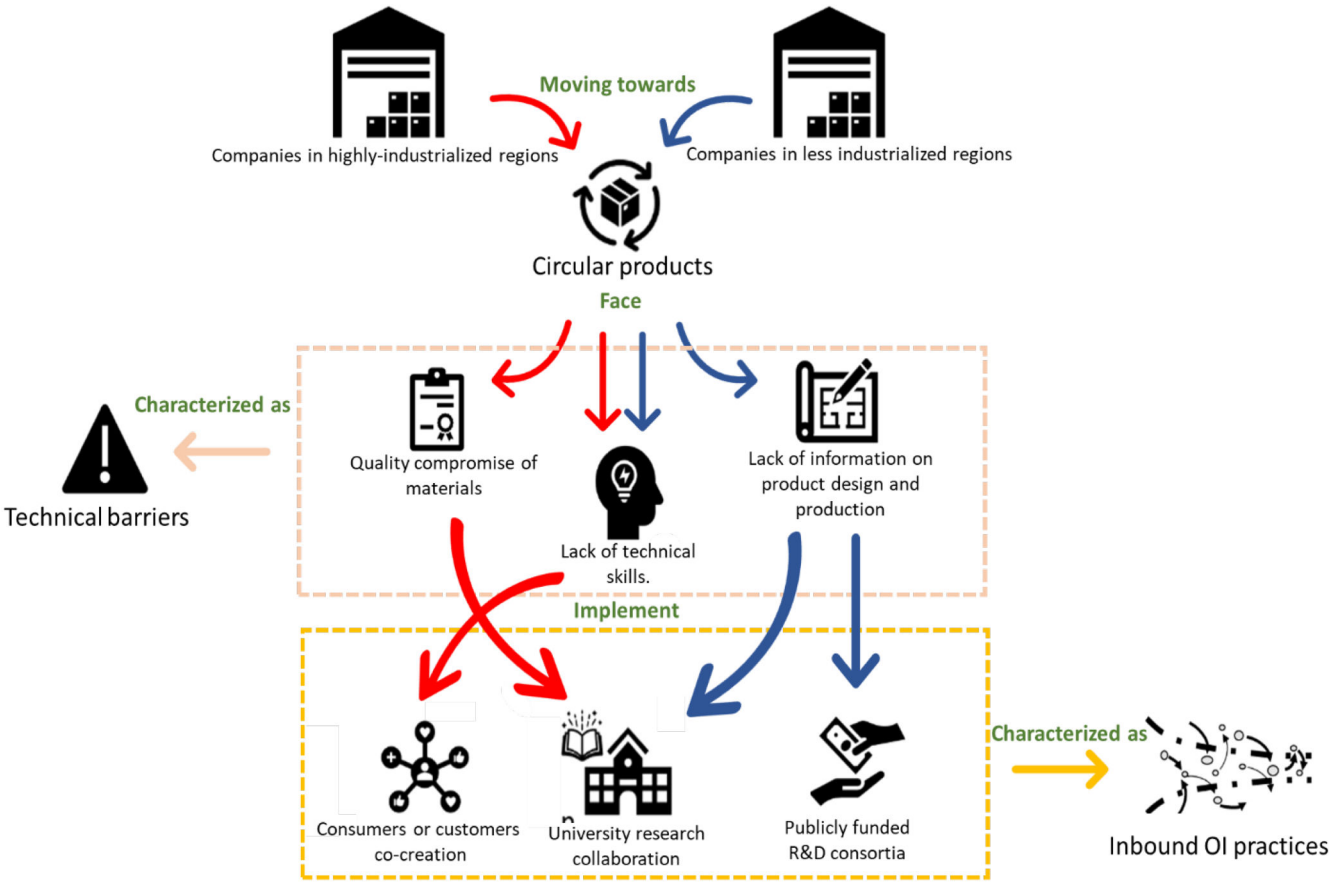

Fig. 5. Companies transitions towards circular products.

and cross-sector partnerships, the research advances theoretical insights into the mechanisms by which OI can enhance CE implementation, bridging gaps in existing literature (Jesus & Jugend, 2021; Sgambaro, Chiaroni, & Urbinati, 2024).

Second, the study highlights the contextual specificity of CE approaches, contrasting the challenges faced in industrialized regions with those in less developed contexts. This regional lens contributes to theories of institutional and systemic dynamics in sustainability transitions, underscoring the interplay between socio-economic conditions and technological advancement in enabling circularity. Such differentiation broadens the scope of CE research by integrating a comparative perspective often underexplored in the literature (Salvador et al., 2022).

Moreover, the investigation into technical hurdles—including insufficient product design information, suboptimal material quality, and skill shortages—provides a nuanced understanding of how operational barriers intersect with broader systemic challenges (Kirchherr et al., 2018). This extends CE theories by linking micro-level technical issues with macro-level ecosystem dynamics, emphasizing the need for integrated, multi-level solutions (Bocken et al., 2016).

Finally, the study positions OI as a critical enabler of CE, offering a theoretical framework to explore its role in fostering innovation that supports circularity. By bridging knowledge from OI and CE domains, this research lays a foundation for future studies to delve deeper into how collaborative innovation networks and stakeholder engagements can accelerate transitions toward a CE.

Managerial and practical implications

This study provides actionable insights for managers striving to move towards circular production, particularly in addressing technical barriers when developing circular products. A critical first step for managers is to develop an acute awareness of the specific issues constraining their transition towards CE. Identifying barriers—such as material quality concerns, knowledge gaps, and skill shortages—offers a realistic and context-specific picture of the challenges at hand. This diagnostic approach not only ensures that managers allocate resources effectively but also orients strategic decisions towards viable solutions tailored to their operational contexts.

Engaging consumers in product innovation can yield valuable market insights and foster trust. For instance, a manufacturing company could launch an interactive platform for customers to share ideas or feedback on sustainable product designs. A successful example is the material handling line of a pilot plant at Company A's production site, which invites customers to collaborate on product development. Such approaches not only enhance product relevance but also align business strategies with consumer sustainability preferences.

Academic partnerships can provide access to expertise and innovative technologies. This is particularly relevant for companies located in less developed regions, where this kind of practice has been less used. For example, a company could partner with a university to develop recyclable materials for composites, as seen in the north of Italy where emphasis on developing sustainable bioplastics has materialized. In less developed regions, managers can initiate joint workshops or research projects with local universities to address skill gaps and technological limitations, advocating for public funding where necessary.

In addition, managers should prioritize training programs to build competencies in circular design and resource-efficient practices. For instance, organizing workshops with experts in lifecycle assessment or resource management can help employees better understand CE principles. Top sustainable companies known for their circular approach invest heavily in employee education on sustainable product design and repair techniques, showcasing the benefits of such initiatives.

Sourcing expertise through public R&D consortia or industrial networks can help companies address technical challenges while sharing costs and risks. For example, managers could join collective projects, which fosters innovation through collaboration among industries, start-ups, and academic partners, driving advancements in sustainable materials and processes. It is worth noting that excessive dependence on government support may also have undesirable effects for the company and markets.

When focusing on circular products, managers should integrate CE principles into the entire product lifecycle, emphasizing design, material sourcing, and end-of-life management. This includes adopting modular designs to facilitate repairability and considering closed-loop systems for material recovery. Moreover, co-creating these solutions with stakeholders, including suppliers and end-users, can significantly enhance product acceptance and functionality.

By implementing these strategies, managers can overcome CE barriers and transition toward circularity more effectively. Recognizing barriers specific to their operational environment—whether related to technical skills, regulatory limitations, or market preferences—allows managers to craft informed and targeted solutions. Ultimately, fostering an ecosystem of collaboration, learning, and innovation will enhance the sustainability and competitiveness of their businesses in a CE.

Conclusions

This study set out to address the overarching question of how companies exploit OI practices to overcome CE barriers while developing Circular Products. Through its three main research goals, the study highlights critical insights into the interplay between OI practices and CE barriers. Stage 1 identified technical barriers as the most significant obstacles hindering the development of circular products, such as skill shortages, knowledge gaps, and material quality concerns. Stage 2 demonstrated that inbound OI practices, such as publicly funded R&D consortia, consumer co-creation, and university collaboration, are particularly effective in addressing these challenges. Stage 3 revealed notable regional disparities in how companies employ OI practices to tackle CE barriers when developing circular products. Firms in highly industrialized regions leverage stringent regulations and robust institutional frameworks to drive innovation, focusing on advanced technologies and stakeholder engagement. In contrast, companies in less developed regions face systemic challenges, including weaker regulatory environments and limited access to expertise, which they address through grassroots collaborations and capacity-building efforts. Despite these differences, the study emphasizes the universal importance of workforce development, technical skill enhancement, and collaborative networks as cornerstones of CE implementation. Ultimately, this research provides a holistic understanding of the role of OI in CE, illustrating how tailored strategies can enable firms across diverse contexts to transform barriers into opportunities, advancing circularity and sustainability objectives.

This research holds theoretical, managerial and practical implications as it has been discussed in the previous sections. In particular, theoretical aspects encompass investigating the CE-OI relationship and the exploitation of OI practices in circular product development, while, in practical terms, the study suggests companies can tackle CE challenges through inbound OI practices, acquiring external knowledge for innovative, high-quality products. Overall, the research highlights the intricate relationship between technical barriers, OI practices, and regional disparities, providing a comprehensive understanding of the journey towards circular production in diverse industrial contexts.

However, the study has limitations, being exploratory and focusing on a limited number of case companies in Italy and Uruguay. Even though previous academic works have adopted similar research approaches, the comparability and, therefore, the generalization of these findings may require particular considerations. In addition, it is worth noting that a narrow perspective on the variety of sectors inspected may be another limitation of this study. Future research can expand on these findings with larger-scale studies involving diverse industries and regions. Longitudinal studies can provide insights into OI's long-term impact on CE. Comparative studies between companies in different contexts can deepen understanding of context-specific barriers and facilitators. Exploring the role of other stakeholders, like suppliers and academic institutions, in the OI process can provide a more comprehensive view of developing circular products. Overall, this study contributes valuable insights at the intersection of CE and OI, offering implications for sustainability scholars and practitioners driving the transition to a CE.

CRediT authorship contribution statement

Juan I. Dorrego-Viera: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Urbinati:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Valentina Lazzarotti:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Annex 1

Interview guiding questions

We are conducting a research study focused on exploring the intersection of Open Innovation practices and Circular Economy within companies. The purpose of this research is to investigate how companies leverage Open Innovation to overcome Circular Economy barriers and drive the development of Circular Products.

Please note that all data collected during this interview will be anonymized and used exclusively for academic research purposes with the necessary data protection measures in place. Your valuable insights and experiences in these areas will contribute significantly to our research efforts and help advance knowledge in the field of Circular Economy and Open Innovation. Thank you for your participation and valuable input in this study.

1. Classification Questions

- Name of the company
- Sector/Industry
- Position/Role within the company
- Number of years working at the company
- Main duties and responsibilities in the company
- Experience with Circular Economy initiatives (# years)
- Experience with innovation practices (# years)
- Main aims or objectives of the company
- Brief description of the business model the company is following

2.0. Circular Economy Interest and Involvement

2.0.1. How would you describe your company's overall sustainability approach and commitment to environmental initiatives?
2.0.2. How would you describe your company's overall interest and involvement in Circular Economy transition?
2.0.3. What specific initiatives or projects has your company undertaken related to Circular Economy?

2.0.4. How important is Circular Product Development within your company's CE transition?
2.0.5. What are the main challenges your company faces in transitioning towards a Circular Economy?

2.1. Technical Barriers

2.1.1. What are the key technical challenges or barriers your company has encountered in transitioning towards a Circular Economy?
2.1.2. How does the lack of crucial information on product design and production impact your circular product development efforts?
2.1.3. In what ways has the lack of technical skills within the workforce hindered your company's circular economy initiatives?
2.1.4. How does the concern over compromising the quality of products when integrating recycled or renewable materials affect your company's approach to Circular Economy?

2.2. Economic Barriers

2.2.1. What financial challenges have you faced in implementing circular processes within your company?
2.2.2. How do high start-up costs for circular initiatives impact your company's decision-making processes?
2.2.3. Have you encountered challenges in fostering effective business-to-business cooperation in the context of Circular Economy practices?
2.2.4. How does the time-consuming and expensive nature of disassembling products for recycling or repurposing affect your company's Circular Economy efforts?

2.3. Context Barriers

2.3.1. What are the main barriers linked to the context where your company operates that hinder the transition towards a Circular Economy?
2.3.2. How do complex supply chains impact your company's Circular Economy initiatives?
2.3.3. In what ways do structural barriers, such as hierarchical patterns restricting innovation and flexibility, affect your company's Circular Economy strategies?
2.3.4. How does marketplace competition and cultural attitudes pose challenges for your company in progressing towards Circular Economy implementation?

3.0. Innovation

3.0.1. How innovative do you think your company is?
3.0.2. What is the role that innovation plays in the transition toward Circular Economy in your company?

3.1. R&D Department and Stakeholder Engagement

3.1.1. Does your company have an R&D department or unit? If yes, how would you describe its size and level of funding?
3.1.2. Can you describe the innovation approach your company predominantly follows - open or closed innovation?
3.1.3. Could you share insights on the stakeholders or partners your company collaborates with for innovation purposes? (e.g., suppliers, customers, universities, research centers, etc.)
3.1.4. How important are external partnerships and collaborations in driving innovation and Circular Economy within your company?
3.1.5. What are some successful examples of open innovation collaborations or partnerships your company has been involved in?
3.1.6. How does your company engage in open innovation practices to drive circular product development and Circular Economy implementation?
3.1.7. How important are external partnerships and collaborations in driving innovation and Circular Economy within your company?

3.2. Open Innovation Practices

3.2.1. How does your company engage in consumer and customer co-creation for product development related to CE implementation barriers?
3.2.2. What role does information networking play in fostering innovation within or outside your company related to CE implementation barriers?
3.2.3. How does your company collaborate with universities for research and innovation purposes related to CE implementation barriers?
3.2.4. Have you participated in publicly funded R&D consortia to drive innovation related to CE implementation barriers?
3.2.5. How does your company contract with external R&D service providers for innovation projects related to CE implementation barriers?
3.2.6. What is your experience with idea and start-up cooperation in driving innovation related to CE implementation barriers?
3.2.7. How does your company handle IP in-licensing for innovation purposes related to CE implementation barriers?
3.2.8. Have you engaged in supplier innovation sharing to drive product development related to CE implementation barriers?
3.2.9. How does crowdsourcing contribute to innovation within your company related to CE implementation barriers?
3.2.10. Have you utilized specialized services from OI intermediaries for innovation projects related to CE implementation barriers?
3.2.11. What joint venture activities have you undertaken with external partners to drive innovation related to CE implementation barriers?
3.2.12. How does your company approach the selling of market-ready products resulting from innovation related to CE implementation barriers?
3.2.13. Have you participated in public standardization processes to drive innovation related to CE implementation barriers?
3.2.14. What is your experience with corporate business incubation and venturing for innovation related to CE implementation barriers?
3.2.15. How does your company handle IP out-licensing and patent selling for innovation purposes related to CE implementation barriers?
3.2.16. Have you made donations to commons or nonprofits to support innovation and sustainability efforts related to CE implementation barriers?
3.2.17. What is your experience with spinoffs as a result of innovation projects related to CE implementation barriers?

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