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DELIVERABLE 5.1.2: MANUAL OF CE INNOVATION

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Executive summary

This Deliverable explores the role of the circular economy (CE) in promoting sustainability, resilience, and innovation across different sectors and geographical areas. The document is structured into multiple chapters, each addressing critical aspects such as CE indicators, innovation in the semiconductor industry, entrepreneurial ecosystems, university contributions, and mapping CE research in Italy.

Specifically, the Deliverable is articulated in two sections. The first one concerns the exploitation of the CE indicators presented in Deliverable 5.1.1 to dig into the dynamics of CE-related innovation in sectors and geographical areas, focusing on the different actors of the innovation ecosystem. The second section focuses instead on selected case studies based on the Made in Italy specializations.

In the first chapter, a new taxonomy for circular patents was developed to classify technologies based on patent descriptions and CPC/IPC codes. Using a keyword approach, the study found 32,385 circular patents (3.19% of total EU patents from 1997 to 2019), significantly expanding the dataset compared to previous methods. The study further explores the relationship between circular patents and imported emissions in the manufacturing sector. The findings indicate that circular patents contribute to reducing greenhouse gas (GHG) emissions associated with imported goods, supporting both climate mitigation and strategic autonomy.

The second chapter focuses on the semiconductor industry, which is critical to emerging digital technologies but heavily reliant on rare earth elements. Many companies still follow a linear production model with limited recycling or waste management strategies. A dataset of patents from 2014–2023 was analyzed to classify CE patents in the semiconductor industry. The research examined national and international collaborations, finding that diverse partnerships enhance CE innovation. A Disruptiveness Index was created to measure the transformative impact of circular patents based on novelty, influence, and inventor diversity. Collaboration between firms, universities, and research institutions significantly enhances patent value by integrating diverse knowledge sources. Regional dynamics show that knowledge networks across regions and borders play a vital role in fostering CE innovations.

Chapter 3 analyzes innovative startups that are essential for CE-driven economic transformation. However, existing metrics do not effectively capture their growth

potential. A predictive analytics approach was used to assess the scaling potential of CE startups in Italy. AI-based classification of startup business models was employed to identify CE-related startups. The study found that CE startups are concentrated in Northern and Central Italy, though Southern regions exhibit a higher proportion of CE-focused ventures relative to total startups. Entrepreneurial ecosystems in Southern Italy show potential for CE growth, requiring targeted policy interventions.

Chapter 4 presents evidence concerning Higher education institutions (HEIs), which may play a critical role in advancing CE through research, teaching, and innovation. The study examines how universities contribute to CE and how sustainability rankings reflect their efforts. A CE Score was proposed to evaluate universities' involvement in CE based on courses, publications, research centers, and patents. The study examined the relationship between sustainability rankings and CE performance, using data from 75 Italian universities (2010–2023). A causal link was found between sustainability rankings and CE performance, demonstrating that universities respond strategically to ranking criteria. While universities improve in ranking metrics, non-measured sustainability initiatives (e.g., patents, spin-offs) tend to decline, indicating a potential misalignment of incentives.

In chapter 5 a novel methodology combining machine learning, language models, and topic modeling is exploited to map CE innovations through patent data. 864,714 European patent families were identified as CE-related, surpassing previous classification methods. CE patents are categorized under five key principles (5Rs: Reduce, Reuse, Recycle, Repair, and Refurbish) and ten technology areas (e.g., Adaptive Materials, Waste Management, Battery Recycling). The analysis found that CE patenting activity has been growing but declined after 2010, aligning with broader green patenting trends. Geographically, CE innovation is concentrated in industrial hubs like Paris, Helsinki, and Milan. The most significant contributions come from chemical manufacturing, special-purpose machinery, and battery technologies. Leading companies include Procter & Gamble, Samsung, Siemens, Robert Bosch, and Novozymes, all of which contribute extensively to CE patents in different domains.

The second section of the report explores case studies on Circular Economy (CE) innovation, focusing on the role of digital platforms, stakeholder engagement, and cognitive biases in CE adoption. It emphasizes the need for collaborative ecosystems, technological advancements, and behavioral insights to accelerate the transition from linear to circular models.

The first chapter explores the Role of Digital Platforms and Ecosystems in CE. Key findings are the following. Digital platforms serve as innovation infrastructures,

fostering knowledge sharing, collaboration, and value co-creation. The study identifies how multi-stakeholder networks leverage digital platforms to support CE transitions. The Italian Circular Economy Stakeholder Platform (ICESP) is highlighted as a successful case of a digital ecosystem facilitating CE initiatives. ICESP fosters collaboration among businesses, research institutions, and policymakers to develop and disseminate best practices for CE. Digital platforms support regulatory compliance, market innovations, and knowledge dissemination, ensuring broader engagement in CE activities.

Chapter 2 analyzes the role of Stakeholder Engagement and Digital Transformation to enable circularity in the Textile Industry. It stresses that the textile industry, known for its environmental impact, can benefit from CE strategies such as reducing waste, reusing materials, and recycling. Digital Technologies (DTs), including blockchain and artificial intelligence, enhance traceability, optimize supply chains, and enable sustainable production. Stakeholder engagement is crucial in integrating DTs into CE business models, promoting transparency, and improving sustainability outcomes. The study presents multiple case studies from Italian luxury fashion firms, demonstrating how collaboration and digitalization facilitate CE transitions. Strategic partnerships between companies, technology providers, and policymakers drive the successful implementation of circular practices in textiles.

The last chapter explores the role of cognitive Biases in the CE transition and the implications for stakeholder engagement and decision-Making. It highlights that cognitive biases may hinder CE adoption by influencing stakeholder decision-making, creating resistance to change, and limiting long-term sustainability commitments. Status quo bias, temporal discounting, and single-action bias are identified as key psychological barriers to CE implementation. Availability bias influences decision-making by prioritizing short-term financial goals over long-term sustainability benefits. Addressing these biases requires targeted interventions such as education, financial incentives, and behavioral nudges to encourage circular business practices. Policymakers and businesses must recognize the role of cognitive biases in shaping attitudes towards CE and design strategies that mitigate these challenges.

In sum this study provides both methodological and empirical contributions to CE research, highlighting the need for improved circularity indicators, fostering CE innovation in key industries, and supporting startups and universities in adopting CE practices. Moreover, it stresses the interconnected role of digital transformation, stakeholder collaboration, and behavioral economics in accelerating CE adoption.

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1. Applied use of CE Indicators

1.1 CE Innovations Pollution and Supply Chain Vulnerabilities: A Study of Patented Technologies effects on the European manufacturing Sector

1.1.1 Introduction

The circular economy is a model of production and consumption characterized by promoting the reuse, repair, and recycling of products and materials, in contrast to the traditional linear economy, which follows a 'take, make, consume, throw away' approach (Bourguignon, 2016). By changing in such a fundamental way the productive paradigm, this economic framework is crucial for the achievement of important sustainability goals such as mitigating climate change and curbing material resources depletion. Indeed, the circular economy minimizes the need for new resource extraction and manufacturing, whose contribution to the global greenhouse gas (GHG) emissions has been estimated reaching 70% of the global level of GHG emissions (Circle Economy, 2021). Additionally, the extension of the life cycle of materials helps in reducing the amount of waste destined to landfills and incineration, further decreasing emissions and environmental pollution.

Given this crucial role of the circular economy for the green transition, the European Union has adopted a Circular Economy Action Plan and defined it as one of the main pillars of the European Green Deal, the EU's program to achieve climate neutrality. In the context of this action plan, the Commission has also developed a circular economy monitoring framework, highlighting the importance of a data-driven monitoring of the progress in the sector and promoting research on the drivers of the CE transition.

Furthermore, the circular economy can play a crucial role in enhancing the EU strategic autonomy. Indeed, reducing the imports' level of raw materials, especially minerals needed for the development and manufacturing of net-zero technologies, can potentially represent a pathway for the establishment of more resilient supply chains and diminishing the reliance on single country suppliers, especially when on countries non-aligned with EU values (Commission, 2023).

The centrality obtained by the Circular Economy for the climate transition highlights the need for comprehensive and accurate circularity indicators. Despite the existence of numerous metrics and indicators – particularly those provided at the EU level through the Circular Economy Monitoring Framework – current circularity measures predominantly emphasize established practices and past performance, such as municipal recycling rates. However, these metrics often fall short in capturing the future potential for advancements driven by innovation, limiting their utility in forecasting progress toward a more circular economy.

This chapter integrates the aforementioned considerations by offering both a methodological and empirical contribution to the study of circular innovation.

From a methodological point of view, Section 1.1.2 develops a novel taxonomy for classifying circular patents, offering a structured framework to simplify the identification of circular technologies and enable more precise assessments of circular innovation. The proposed taxonomy classifies patents as circular if they pertain to wastewater treatment and waste management technologies or if their titles and abstracts reveal a strong alignment with circular economy principles.

From an empirical point of view, in Section 3, we will provide a preliminary description of the main characteristics of EU circular patents in terms of sectoral and geographical distribution together with their evolution over time. Instead, in Section 4 we present an analysis conducted to shed light on the role that circular economy innovations have in inducing a reduction in the level of imported emissions, a metrics that we deem as particularly suitable to investigate the twofold role of CE innovations, i.e., to support climate change mitigation and enhancing strategic autonomy. Using a dataset of circular patents identified via the novel methodology described in Section 2, a panel data model at country-sector level will be applied to analyze the potential role of circular economy innovations in reducing imported GHG emissions and, more broadly, the EU carbon footprint.

Section 5 will conclude and discuss possible research trajectories concerning the impact of circular patents on both emissions and import patterns. Indeed, it will be described the possibility of investigating emissions typologies other than the imported ones, e.g., directly imputable emissions, and by focusing the analysis on the importation of particular typologies of products, such as the ones classified by the European Union as “critical raw materials”.

1.1.2 Identification of circular patents

Unlike green technologies, which have established CPC and IPC classifications (Angelucci, Hurtado-Albir, & Volpe, 2018; Veefkind, Hurtado-Albir, Angelucci, Karachalios, & Thumm, 2012), circular technologies lack a comparable standardized framework. To date, the literature has primarily identified circular patents through wastewater treatment and waste management (hereafter referred to as "waste") patents (Portillo-Tarragona, Scarpellini, & Marìn-Vinuesa, 2024; Fusillo, Quatraro, & Santhià, 2021; Marino & Pariso, 2020). While waste patents undoubtedly align with circular principles, they represent only a subset of the broader spectrum of circular innovations. This limitation underscores the need to develop a comprehensive taxonomy for classifying circular patents.

The proposed taxonomy determines whether a patent qualifies as circular by utilizing both the information embedded in its CPC and IPC classifications and the content of its title and abstract, as illustrated in Figure 1. Specifically, a patent is classified as circular if it meets at least one of the following two criteria: it is identified as a waste patent according to its IPC or CPC codes, or its title and abstract collectively include

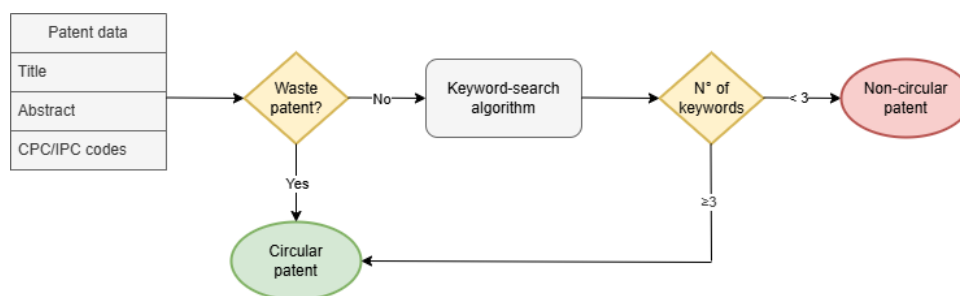


Figure 1: Flowchart of the algorithm for the identification of circular patents.

at least three keywords from a predefined and carefully curated set.

The keyword set was developed through a rigorous refinement process applied to an initial collection of terms related to the concept of circular economy and its principles. This original set was compiled using natural language processing techniques to extract terms from diverse sources. These sources included scientifically established concepts such as the 10R framework, titles and abstracts of a selected set of waste patents, and the International Energy Agency's (IEA) green technologies database. By drawing from multiple sources, the methodology ensured a comprehensive blend of scientifically recognized circular principles, patent-specific terminology, and names of technologies that can play a pivotal role in advancing the transition to a circular economy. The resulting initial set of terms has been manually validated to ensure adherence to circular principles, avoiding duplicates.

The initial set of circular terms was refined by optimizing its effectiveness in identifying circular patents using a manually classified dataset of 1,000 Italian patents. These patents were categorized as either circular or non-circular and sampled from the full population of 75,667 Italian patents granted between 1997 and 2019, ensuring representativity across filing years and technological classes. The refinement process focused on improving the algorithm's performance by testing it against this validated sample.

The original set of circular terms was adjusted in three ways. The first avenue consisted in expanding the set by including relevant terms present in the titles and abstracts of patents manually classified as circular but missed by the algorithm (false negatives). The second strategy focused on introducing stop-words, which reduce the keyword count by one if detected, to improve specificity and reduce false positives by excluding terms frequently found in non-circular patents. Finally, terms with a relative frequency in circular patents versus non-circular ones below 1.3 have been removed. The final set of keywords is provided in Table 1.

Source	Keywords
CE framework	circular, efficiency, lifecycle, lifespan, lifetime, long-lasting, recover, recycle, reduce, refurbish, refuse, regenerate, remanufacture, renewable, repair, repurpose, restore, rethink, reuse, upcycle
Waste patents	anaerobic, bio, biomass, carbon (capture), collect, compost, degradable, digester, emissions, filter, lignocellulose, manure, maintenance, natural, optimization, organic, pasteurization, purification, sludge, treatment, waste, water
IEA database	absorption, conversion, decontamination, energy, heat pump, latent heat (storage), photovoltaics, platooning, pollutant, remediation, separation, solar, wave, wind
False positives	abatement, combined, concurrent, depuration, ecologic, impurity, modular, municipal, preserve, recirculate, recondition, recuperate, retrofit, reversible, scrap, shelf-life, sterilization, toxic
Stop-words	anemia, antibiotic, biocide, biological particles, biological tissues, biomolecules, blood, cleaning, dental, diagnosis, disease, dispense, DNA, electromagnetic, equalizing (filter), gun, human body, image, infection, laser, lesion, memory storage, medical, microwave, MPEG, pathology, patient, pharma, prophylaxis, prosthesis, radiation, surgical, symptom, syndrome, therapeutic, tumor, video, ultrasound, wash

Table 1: Final set of keywords by source.

Additionally, the manually validated dataset was used to optimize two key parameters of the algorithm: the text source for keyword searches (titles and abstracts together, titles only, or abstracts only) and the minimum keyword count required to classify a patent as circular. The algorithm was tested across thresholds of 1 to 5 keywords and for different text sources. The optimal configuration, the one entailing searching both titles and abstracts and requiring at least three keywords for classification, achieved

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the best performance, with an accuracy of 95.9%, a precision of 83.72%, and a recall of 51.43%.

1.1.3 Descriptives

The following analyses refer to patents granted between 1997 and 2019 to EU companies. The dataset consists of 1,013,829 total patents, of which 107,384 (approximately 10.59%) are classified as green patents according to their CPC and IPC codes while 6,696 (about 0.66%) relate to wastewater treatment and waste management technologies which have often been employed as a proxy of circular patenting activity in the literature. By applying the methodology presented in Section 1.1.2, we find 32,385 circular patents corresponding to approximately 3.19% of total patents; therefore, the proposed taxonomy of circular patents allows to significantly enlarge the set of circular patents (+383%). We find significant variability in the percentage of circular patents by country ranging from values below 3% in Serbia (2.32%) and Germany (2.72%) to values above 10% in Lithuania (10.15%), Romania (11.84%), and Slovakia (13.12%).

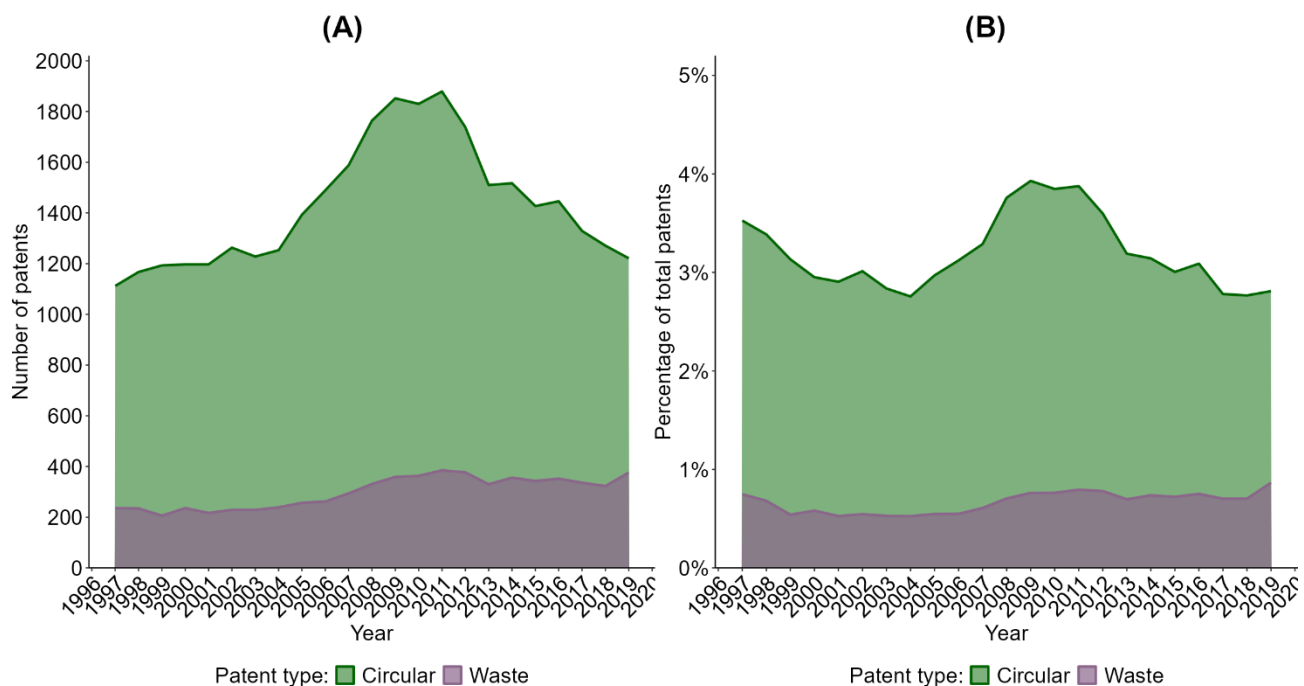


Figure 2: Number of circular and waste patents by year (panel (A)) and percentage of circular and waste patents with respect to total patents by year (panel (B)), period 1997–2019.

Figure 2 reports the number of circular and waste patents by year of earliest application in panel (A) together with their corresponding percentage with respect to total patent in panel (B). Panel (A) highlights that the number of circular patents

granted in the EU peaked in the early 2010s to about 1,850 circular patents per year. However, since then, there has been a constant decline with the number of circular patents falling below 1,200 patents per year by 2019. This trend mirrors the trajectory of total patents granted, which experienced a steady increase before peaking at 48,481 patents annually in 2011, followed by a gradual decline to 43,449 patents per year by 2019 in line with the findings of previous research (Criscuolo, Dechezlepretre, & Lalanne, 2023). In contrast, the trend for patents related to waste has been smoother throughout the sample period and has shown a slight upward trend over the period considered. Similar considerations hold when considering the percentage of circular and waste patents relative to the total number of patents as shown in panel (B) of Figure 2. From this point of view the early increase in the number of circular patents can be interpreted more as an overall increase in patenting activity during the early 2000s rather than an increase in the level of circularity which has been declining in the early 2000s and recovering in the late 2000s. Instead, the slowdown in circular innovation after 2010 seems to be driven by a combination between a decrease in total patenting activity as mentioned earlier and an overall decrease in the level of circularity. It is worth mentioning that the level of circularity seems to have stabilized to around 3% of total patents since 2017.

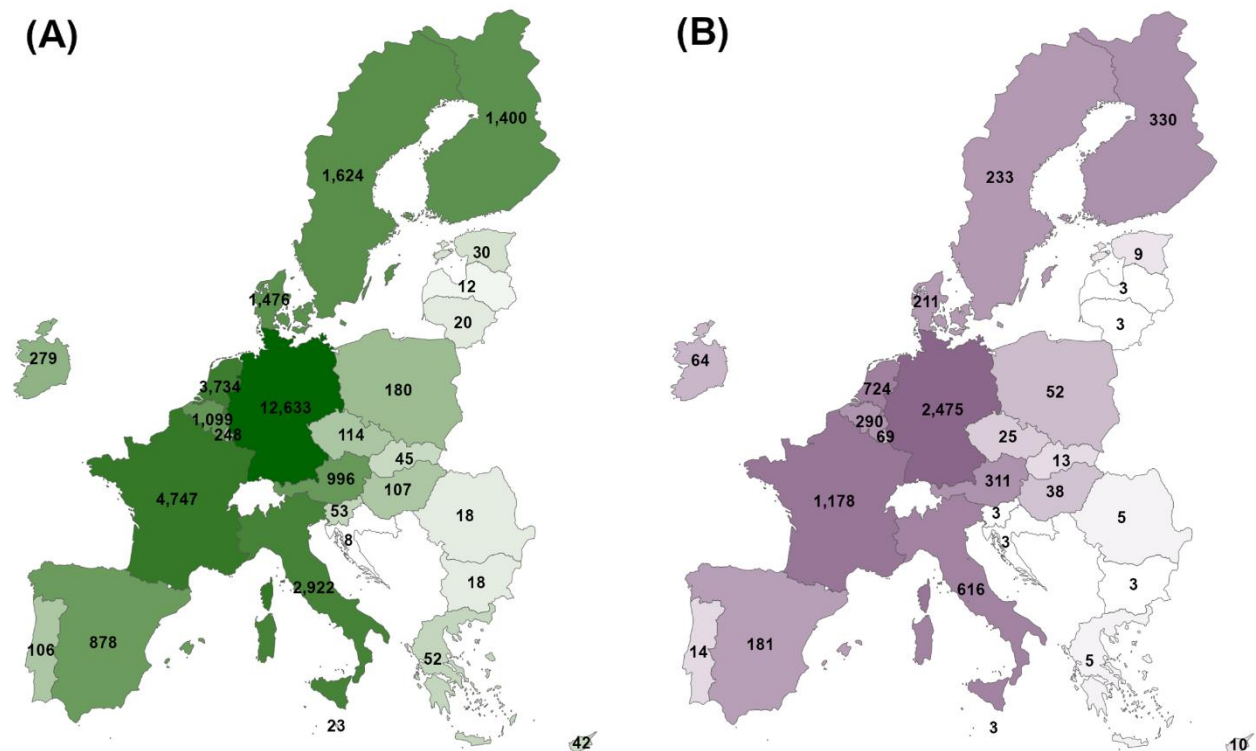


Figure 3: Number of circular (panel (A)) and waste (panel (B)) patents by country, cumulated over the period 1997-2019.

The total number of circular (panel (A)) and waste (panel (B)) patents by country reported in Figure 3 highlights how relatively smaller countries such as the Netherlands are important hubs for the circular innovation activity, surpassing even in absolute terms greater and more populated nations such as Spain and Italy, although Germany remains the leading actor in the sector, also given its general predominance in the manufacturing sector. The geographical distribution of the patents related to waste does not present crucial differences, although it can be noted a greater weight of France in this subsample.

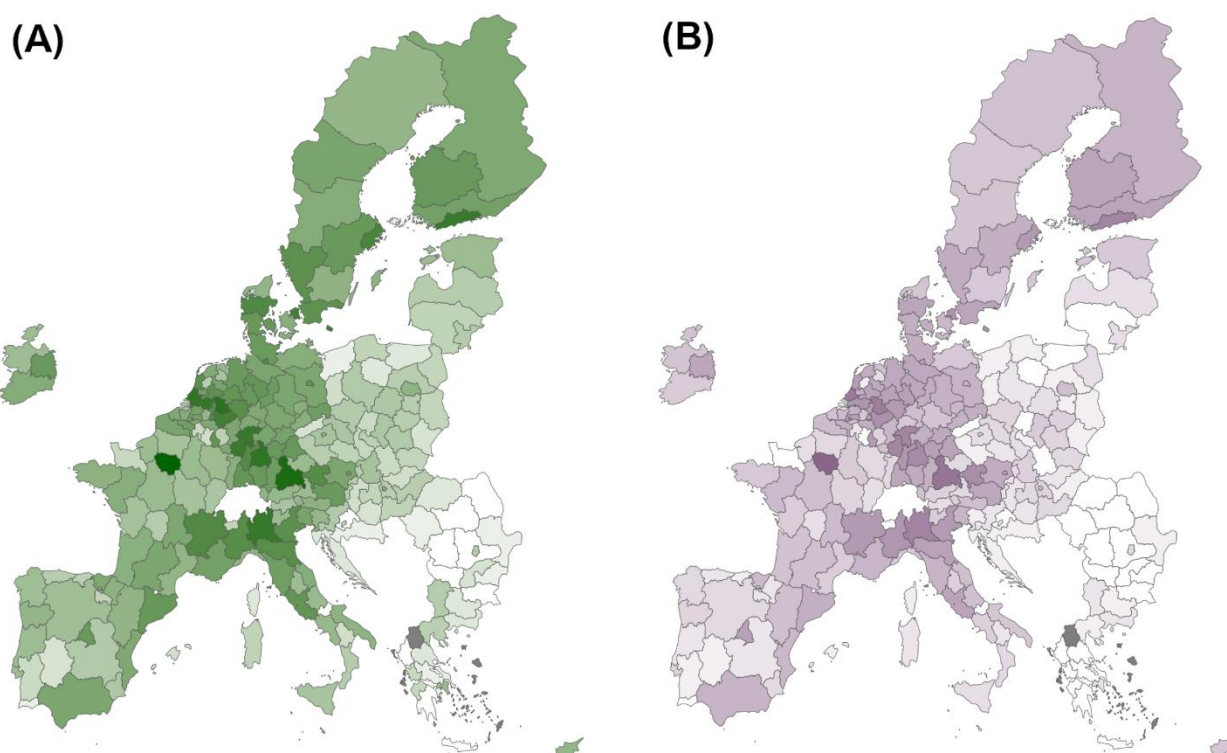


Figure 4: Number of circular (panel (A)) and waste (panel (B)) patents by NUTS 2, cumulated over the period 1997–2019.

Looking at the geographical distribution at the NUTS2 level as shown in figure 4, it is quite clear the presence of a clustering of circular innovations in the areas with significant economic activity and industrial concentration. Indeed, the areas with a higher concentration are the regions across the border between Luxembourg, Netherlands and Germany, the Western and Southern areas of Germany, the North of Italy, and the Ile-de-France.

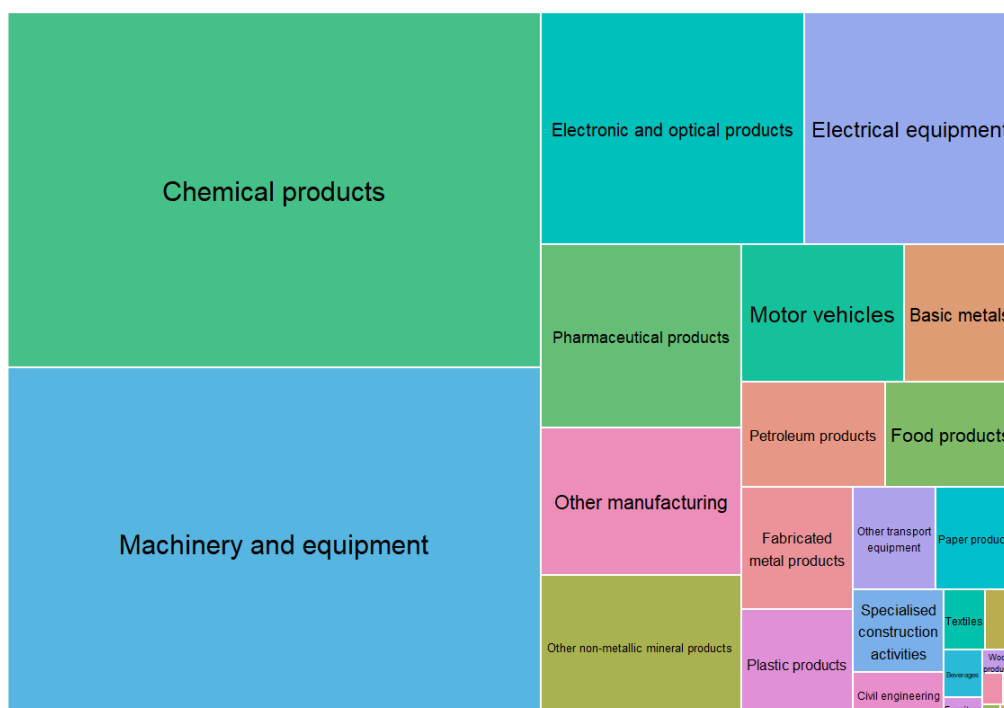


Figure 5: Sectoral distribution of circular patents, period 1997-2019.

Figure 5 reports the distribution of circular patents by 2-digits NACE codes associated by PATSTAT to each patent following the correspondence between IPC and NACE codes developed by EUROSTAT (Van Looy, Vereyden, & Schmoch, 2015). Although there is no assurance of a perfect correspondence between the assigned NACE code and the actual firm's economic sector, it can be an important indicator of the sectors affected by the innovation itself. The two most important sectors are by far the Chemical sector (25.04% of total circular patents) and the "Machinery and equipment" sector (24.69%) followed by "Electronic and optical products" (8.09%). It is worth mentioning that there is significant variability in the level of circularity of the different sectors. The highest levels of circularity – measured as number of sectoral circular patents over total sectoral patents – are achieved by the "Petroleum products" sector with 28.04% of the sector patents being classified as circular, followed by "Paper products" (12.95%), "Chemical products" (10.21%), and "Beverages" (9.47%). Instead, "Wearing apparel" (1.04%), Computer programming (1.15%), and "Electronic and optical products" (1.19%) appear among the least circular sectors.

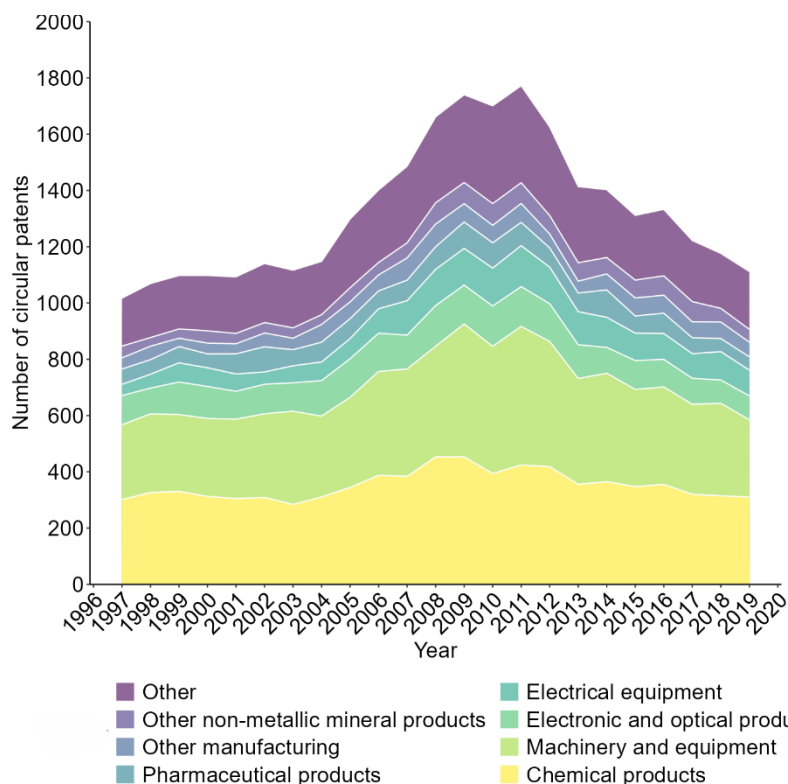


Figure 6: Time series of the number of circular patents by sector, period 1997-2019.

Finally, Figure 6 reports the evolution over time of the number of circular patents by economic sector. The figure reports the top 7 sectors, while the remaining ones are combined in a single “Other” sector. This breakdown highlights that most of the variability in the time series of circular patents is determined by the “Machinery and equipment” and the smaller sectors included in the “Other” category, while the other sectors present nearly stable or at least less marked patterns.

1.1.4 Application

The keyword-search algorithm described in Section 2 enables us to explore novel research questions concerning the effects of circular innovations. Specifically, the following analysis examines the relationship between circular patents and imported emissions in the manufacturing sector. As discussed below, the decision to focus on the manufacturing sector is partially driven by data availability issues. On the one hand, this choice can be seen as a limitation of the proposed study, as other sectors in the economy are also likely to be affected by circular innovations. On the other hand, the manufacturing sector seems a particularly interesting candidate for

studying this topic, due to its high emission intensity and significant dependence on imported raw materials and intermediate goods.

Our analysis touches on the multiple emerging literature streams investigating the different interlinkages between the circular economy and the topics of sustainability and trade. From a methodological perspective, this analysis contributes to the vast literature studying the best metrics and tools to monitor the progress on the circular economy in terms of adoption and innovations (Moraga, et al., 2019; Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019) following the studies adopting Natural Language Processing techniques (Borms, et al., 2024).

In the following application, we will add evidence also to the existing body of literature on the role of the circular economy in contributing to the green transition, in particular in terms of GHG emissions reductions (Cantzler, et al., 2020; Rommens, et al., 2024). The focus on the imported emissions involves also the area of study regarding the effects of the circular economy on trade, a multifaceted and partly unexplored field (Yamaguchi, 2021). Understanding this relationship has important implications for shaping policies aimed at enhancing strategic autonomy and reducing dependence on imported primary raw materials, particularly because the evidence on the extent to which a more circular economy can contribute to these goals remains inconclusive (Dussaux & Glachant, 2018; Baldassarre, 2025).

The proposed analysis relies on two primary data sources: PATSTAT (2023 Spring edition) and Eurostat. From PATSTAT, we extract data on patents filed with the European Patent Office (EPO) over the period 1997–2019. The countries considered at this stage are: Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Spain and Sweden. Our focus is on circular patents, which are categorized as detailed in Section 2. The PATSTAT database enables us to link these patents to specific manufacturing industries. More specifically, it includes information about the extent to which a patent application pertains to one or more industries within the manufacturing sector, based on the mapping of IPC technological codes to NACE codes associated with manufacturing industries. By integrating this information, we construct a panel dataset at the country–sector level, capturing the number of circular patents associated with particular manufacturing industries. Table 2 presents the breakdown of the sectors included in the analysis.

NACE Code	Description
C10-C12	Manufacture of food products; beverages and tobacco products
C13-C15	Manufacture of textiles, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31-C32	Manufacture of furniture; other manufacturing
C33	Repair and installation of machinery and equipment

Table 2: Sectors considered in the analysis.

Eurostat provides data on greenhouse gas emissions footprints, disaggregated by country, sector, and year covering the time period 2010–2019. The greenhouse gas emissions footprint reflects the total emissions generated across the entire production chain of goods and services that are ultimately consumed or invested in a specific sector within a country. These emissions are thus ‘embodied’ in the products and services traded in the destination country.

By combining these datasets, we investigate the relationship between imported emissions and circular innovations. Figure 7 and 8 show the evolution of the average number of circular patents per sector and the average amount of emissions imported per sector (measured in thousands of tons) by country and year for the countries considered in the analysis. Figure 7 shows a decline in the number of circular patents in the average sector in most countries, which is particularly evident in Germany. In 2010 for the average manufacturing sector in Germany we could observe more than 35 patents classified as circular, with this number that drops to roughly 20 in 2019. A similar trend can be observed for France, while in other countries the trend appears to be more stable. These results are in line with the

evidence presented in Section 2 and more in general with the decline in “green” patenting observed after 2010 (León, 2023). Figure 8 highlights that, during the period of interest, the average sector in most European countries was importing a lower amount of emissions. This is particularly true for the four biggest economies in Europe (measured with GDP), i.e. Germany, France, Italy and Spain. As one would expect, these are the four countries that import more emissions, but they are also the ones that reduced the most the amount of emissions imported.

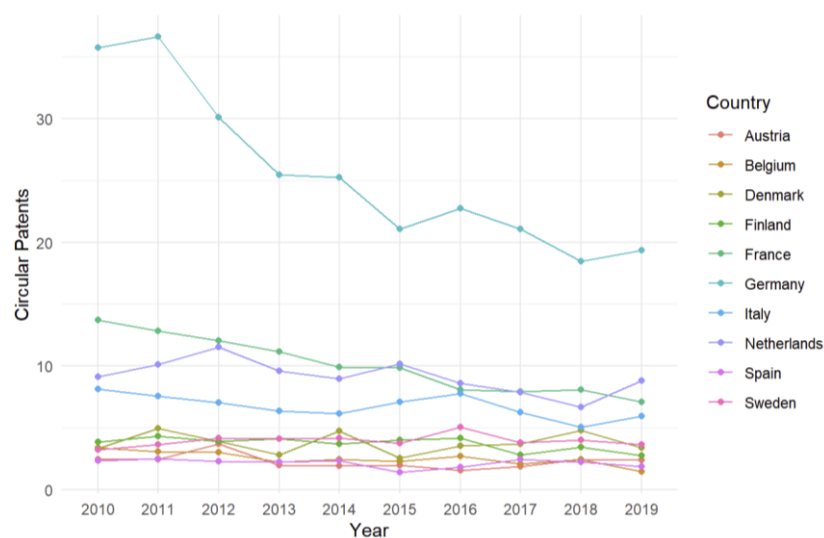


Figure 7: Average number of circular patents per sector (by year and country)

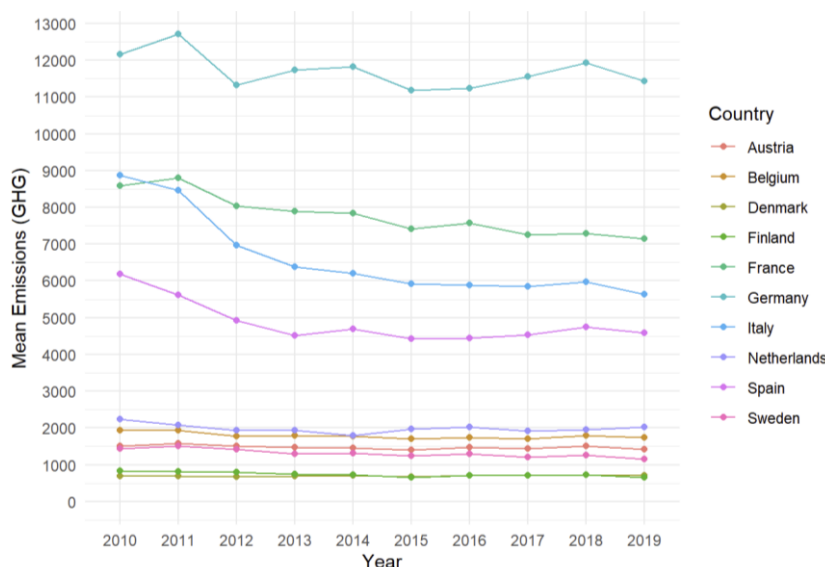


Figure 8: Mean number of circular patents per sector in thousands of tons (by year and country)

To investigate this topic, we construct a panel data set at the country–sector level for manufacturing industries in various European countries. Having done that, we estimate the following model:

$$\text{Log}(\text{ImportedGHG}_{s,c,t}) = \beta_1 \text{CircularPatents}_{s,c,t} + \beta_2 \mathbf{X}_{s,c,t} + u_{s,c} + T_t + N_{(s \times t)} + e_{s,c,t} \quad (1)$$

The main coefficient of interest is β_1 , which captures the relationship between circular innovations developed in sector s in country c and year t ($\text{CircularPatents}_{s,c,t}$) and its greenhouse gas emissions footprint ($\text{ImportedGHG}_{s,c,t}$). $\mathbf{X}_{s,c,t}$ is a vector of other sector–country level control variables. To be more precise, we control for the environmental taxes levied on sector s ¹ and the logarithm of its production value². The former allows us to control for the use of market-based instruments to stimulate the adoption of cleaner production process, while the latter is a proxy for economic activity in the sector. Finally, we include fixed effects for the sector–country combination ($u_{s,c}$), the year and the interaction between the sector and the year fixed effect. The latter allows the time trend to differ for different sectors, helping us capture sector-specific shocks that impact the trend of the dependent variable. Following Cameron and Miller (2015), we cluster standard errors to account for potential intra-cluster correlation.

The results from the estimation of model (1) are presented in Table 3. As we can see, the number of circular patents developed for a sector is negatively related to greenhouse gas emissions imported by that sector. This result is robust across different specification, with the magnitude of the estimated coefficient that remains stable across different columns. Commenting briefly on the other two control variables, which are present only in the model presented in column (3), we see that they also are statistically significant and have the expected sign. Environmental taxes are negatively correlated with imported emissions, possibly due to the fact that they foster the adoption of “cleaner” production process. The value of production is instead positively correlated with imported emissions. Since we control for sector-specific characteristics, this can be interpreted as showing that higher levels of production are associated with more imported emissions. Note also that the presence of missing values for these additional control variables is the reason for the difference in the number of observations from column (1) and (2) to column (3).

¹ Source: [Statistics | Eurostat](#)

² Source: [Statistics | Eurostat](#)

These results demonstrate how the indicator proposed in Section 2 can be applied to conduct empirical analyses of interest to policymakers focused on circular economy and circular innovations.

Variables	(1)	(2)	(3)
Number of Circular Patents	-0.0007*** (0.0002)	-0.0006*** (0.0002)	-0.0005** (0.0002)
Environmental Taxes	-	-	-0.0002*** (0.00006)
Log of Production Value	-	-	0.1374*** (0.0504)
Year F.E.	Yes	Yes	Yes
Sector*Year F.E.	No	Yes	Yes
Observations	1900	1900	1801

Table 3: Fixed effect estimates of Model (1). Standard errors are clustered at the sector-country level and reported in parentheses.

1.1.5 Next steps

Overall, this work provides a dual contribution: methodologically, by developing a novel tool to monitor circular economy innovations addressing important gaps in the existing literature, and empirically, by offering new insights into the geographic, temporal, and sectoral dynamics of circular patents and their environmental impact. These findings underscore the importance of fostering circular innovation to address pressing sustainability challenges and transition towards a more circular and low-emission economy.

This study proposes a novel keyword-search algorithm to classify the patents as circular by combining information from their classification codes with the presence of keywords in their titles and abstracts. This keyword set was derived from diverse institutional and academic sources and was refined using a sample of Italian patents. Applying this algorithm to all patents granted to EU companies with filing years between 1997 and 2019, the study classified as circular the 3.19% of the total amount of patents, a significant expansion compared to the results obtained by employing standard indicators used in the literature (circa 0.66%). The descriptive analysis revealed an initial rise in circular patenting activity followed by a sharp decline after 2010. Geographically, circular patenting appears concentrated in densely populated areas and key economic hubs, while from a sectoral perspective, the Chemical products industry emerged as the leading sector. This novel dataset was used to investigate the impact of circular patents on imported emissions across a subset of

EU countries, indicating a positive and significant contribution of these patents to reducing imported emissions, aligning with theoretical predictions.

The proposed analysis can be extended in many directions. For instance, the empirical framework and identification strategy could be enhanced to address questions of causality by employing an instrumental variable approach, although more research would be needed to identify a suitable instrument. Additionally, these findings highlight the possibility for a deeper exploration of the relationship between circular innovations, emission intensity, and import patterns at the sectoral level, for example by investigating whether the presence of circular innovations in a specific sector contributes to a reduction on the sector's importations of primary raw materials. Such an analysis would not only improve our understanding of the underlying mechanisms driving the results observed in Section 4 but also provide valuable insights into issues with direct policy relevance. For instance, understanding the influence of circular economy patents on import patterns is vital for evaluating their potential contribution the EU's goal of enhancing its strategic autonomy, strengthen economic resilience, supporting at the same time environmental and social sustainability. By exploiting information at the sectoral and country level, it would be possible to also focus the attention on the effects of circular economy innovations on the imports of specific products and materials deemed as critical for the supply of net-zero technologies, assessing the capacity of such innovations to shape the international supply chains and the path to EU's carbon neutrality.

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1.2 CE Innovation in the semiconductor industry. The role of national and international collaboration

1.2.1 Introduction

In recent years, both businesses and societies have grappled with complex challenges that are pivotal to societal welfare, such as providing high-quality healthcare to a growing population and addressing climate change (Liu et al., 2023). As these challenges intensify, emerging digital technologies have become crucial in promoting resource efficiency and facilitating the circulation of excess resources across various stakeholders, thereby supporting sustainable business models (Blackburn et al., 2023). Within this context of the semiconductor industry which stands at a critical juncture. It is the backbone of emerging digital technologies and, thus, key to addressing grand challenges. A major concern in the semiconductor industry is the high reliance on rare earth and specialty elements (RESE) in advanced semiconductor components, which are essential for developing high-tech, emerging technologies (O'Connor et al., 2016). Moreover, many semiconductor companies still operate within a linear economy model – take, make, dispose – with only limited remanufacturing and waste management strategies (O'Connor et al., 2016). We propose that these challenges can be managed by integrating circular practices that promote resource conservation and reduce environmental impact. Circularity involves a multifaceted approach, including design for longevity, reparability, remanufacturing, and recycling (Circular Economy Action Plan, 2020). Adhering to these principles – waste reduction, resource reutilization, and sustainable production-consumption systems – circularity provides a comprehensive framework for achieving economic prosperity alongside environmental conservation (Kirchherr et al., 2017; Parte & Alberca, 2023).

1.2.2 Data

The central focus of this research revolves around investigating the CE innovations within the Semiconductor Equipment manufacturers located in Europe, and extracted from the Orbis database (Bureau Van Dijk). In our study the innovation activities are proxied by patents granted to these companies within the period 2014–2023 and

extracted from Orbis IP database. We then classify the patent into Circular patents following the procedure described below.

Identification of Semiconductor Equipment Manufacturers in Europe

Our database refers to Semiconductor Equipment manufacturers located in Europe which are identified using the respective NACE/NAICS codes combined with specific keywords and extracted from the Orbis database (Bureau Van Dijk). There are a total of 895 companies within the SEM sector in Europe.

Type	Criteria
NAICS 2017 (All codes)	333242 - Semiconductor Machinery Manufacturing
NACE Rev. 2 (All codes)	2651 - Manufacture of instruments and appliances for measuring, testing and navigation
NACE Rev. 2 (All codes)	2670 - Manufacture of optical instruments and photographic equipment
NACE Rev. 2 (All codes)	2790 - Manufacture of other electrical equipment
NACE Rev. 2 (All codes)	2899 - Manufacture of other special-purpose machinery
NAICS 2017 (All codes)	333318 - Other Commercial and Service Industry Machinery Manufacturing
NAICS 2017 (All codes)	334515 - Instrument Manufacturing for Measuring and Testing Electricity and Electrical Signals

US SIC (Primary codes only)	3699 - Electrical machinery, equipment, and supplies, not elsewhere specified
NACE Rev. 2 (All codes)	2611 - Manufacture of electronic components
US SIC (All codes)	3674 - Semiconductors and related devices

Identification of Circular Patents

We develop a methodology for classifying their CE patents using both the specific IPC and CPC codes (e.g., Giglio et al., 2021; Portillo-Tarragona et al., 2022). Once we identify the CE patents, we group these patents in terms of their CE technological classification, namely "Remanufacturing", "Recovery of Resource and Energy", "Reuse of Energy and Resource", "Recycling", "Regenerating", "Repairing and Refurbish", "Refuse Management", "Resource and Energy Optimisation", and "Waste reduction and Sustainable Production".

CE Technology Classification	Related IPC/CPC codes (4 digits)
Remanufacturing	C04B; Y02W
Recovery of Resource and Energy	C02F; D01F; D21F
Reuse of Energy and Resource	B29C; B29C; C04B
Recycling	Y02W; C03B
Regenerating	B01J; H01J
Repairing and Refurbish	H01J; H01K
Refuse Management	C04B; B03B; B65F; Y02W
Resource and Energy Optimisation	Y02B
Waste reduction and Sustainable Production	Y02P; G01R; G05B

1.2.3 The role of national and international collaboration in circular innovation

Emerging digital technologies play a pivotal role in addressing grand societal challenges. However, their development requires substantial resources, particularly energy, which exacerbates environmental challenges. This phenomenon, often referred to as the "dark side of digital innovation," highlights a paradox: while digital technologies can mitigate environmental issues, their development also contributes to such problems. This paper examines the strategies employed by European Semiconductor Equipment Manufacturers (SEMs) to navigate the paradox of fostering digital innovation while transitioning to circularity. Specifically, we investigate how these firms collaborate with diverse actors, including other companies, research institutions, universities, individuals, and governmental bodies—to adapt to different stages of the innovative lifecycle.

For this study, we concentrate on innovative SEMs developing circular innovations. Once we identified innovations linked to circular economy practices, we categorized them into waste reduction and sustainable production, energy and material reuse, resource and energy optimization, and resource and energy recovery. We analyze the inventors associated with these categories and track their evolution over time. Additionally, we conduct a comparative analysis of collaboration patterns between circular innovations and those embodying digital/ICT elements. This study provides nuanced insights into how SEMs adapt their collaborative networks to address the dual challenge of advancing digital innovation and achieving environmental sustainability.

Indicators of technological and actor diversity

To investigate the entities and actors driving innovation at the intersection of digital technologies and circular innovations, as well as to understand the dynamics of their collaborations, we construct indexes capturing technological diversity and collaboration diversity. Additionally, we develop indices to assess various aspects of multi-actor collaborations.

- **Technological Diversity Index (TDI):** TDI measures the breadth and variety of technologies developed by Semiconductor Equipment Manufacturer (SEM) firms. A high TDI within a patent suggests significant convergence across diverse technological fields, reflecting the proliferation of new and varied technologies. The index is calculated using Shannon's Diversity Index, based on the distribution

of International Patent Classification (IPC) or Cooperative Patent Classification (CPC) codes in a patent.

- **Actor Diversity Index (ADI):** ADI evaluates the diversity of collaborative actors contributing to the development of advanced technologies. These collaborations often involve a combination of expertise, resources, and knowledge from varied entities. The index accounts for both the variety and geographical distribution of actors involved in patenting activities. ADI is also calculated using Shannon's Diversity Index, where we analyze the different variety and geographical distributions of actors.

These indices provide quantitative measures of technological and actor diversity, offering critical insights into the collaboration patterns driving innovation in SEM firms.

1.2.4 The role of collaborations on disruptiveness of circular innovations

Circular innovations are often disruptive innovations as they often challenge traditional linear business models, driving industries toward more sustainable systems (Kivimaa et al., 2020). The disruptive nature of these innovations can marginalize incumbent actors unable to adapt, creating opportunities for new entrants to develop advanced sustainable technologies (Skeete, 2018). Incumbent firms, therefore, must reconfigure their innovation strategies, establish new collaborations, and develop capabilities to maintain competitiveness (Grillitsch et al., 2019; Saouma et al., 2024). In Paper 2, we introduce a "Disruptiveness Index" tailored to measure the multifaceted disruptiveness of innovations within the Circular Economy (CE) framework. This comprehensive approach provides a nuanced understanding of how circular innovations disrupt existing socio-technical systems. Grounded in an extensive review of technological innovation and sustainability literature, this index serves as a robust tool for assessing the transformative potential of circular innovations. Additionally, by examining the characteristics of inventors (e.g., firms, independent inventors, research centers, and universities) and inventor networks (including centrality, closeness, and betweenness), we explore their contributions to the disruptiveness of circular innovations compared to non-circular innovations. Geels (2004) emphasizes the importance of aligned actors and networks for scaling niche innovations, such as circular innovations, making the analysis of inventor networks essential to understanding their role in fostering disruptive changes. This study contributes to the broader discourse on sustainability-oriented policy frameworks, providing an integrated perspective on how circular innovations

can align economic and environmental objectives. By addressing critical gaps in understanding the dynamics of disruptiveness, our research offers strategic guidance for advancing sustainable development through circular innovations in the semiconductor industry.

To evaluate the disruptiveness of circular (vs. non-circular) innovations within the Semiconductor Equipment Manufacturing (SEM) sector, we developed a composite "Disruption Index" that integrates four critical dimensions: Technological Novelty, Technological Influence, Technological Diversity, and Inventor Diversity. This index provides a comprehensive and nuanced measure of disruptiveness by addressing gaps in existing methodologies.

- **Technological Novelty (TN):** Technological novelty refers to the introduction of significantly distinct technologies, concepts, or processes that disrupt existing paradigms and foster competitive advantages, thereby driving firm growth (Petruzzelli et al., 2015). Traditional methods for measuring novelty often rely on patent classification and citation data, which can inaccurately reflect the technical content of patents (Arts et al., 2021). To address these limitations, we employ an advanced approach combining Cosine and Jaccard similarities. These methods analyze both the abstract and claims of patents, capturing the significance and presence of unique terms (Fontana et al., 2020).
- **Technological influence (TI):** Technological Influence is assessed through patent citations, which reflect the impact of a patent on subsequent technological developments (Nemet & Johnson, 2012). To account for indirect influence, we apply a discount function based on the generational distance of citations (Corredoira & Banerjee, 2015). Additionally, we normalize citations per year to accommodate newer patents with fewer citation opportunities (Aristodemou & Tietze, 2018).
- **Technological Diversity (TD):** Technological diversity reflects a patent's applicability across various fields, emphasizing its potential for widespread market impact (Song et al., 2017). We use Shannon's Diversity Index to measure TD, based on the distribution of IPC/CPC codes within a patent:
- **Inventor Diversity (ID):** Inventor diversity highlights the variety of actors involved in patent creation, with diverse teams often producing higher-quality and more impactful patents (Brixy et al., 2020). We apply Shannon's Diversity Index to assess the distribution of inventor types and their geographical locations:
- **Disruption Index (DI):** To calculate DI by combining all the above indexes by normalizing all indices to a common scale (0–1) and average them.

This comprehensive metric provides actionable insights into the disruptiveness of innovations in the SEM sector, emphasizing the interplay between technological and collaborative dynamics.

1.2.5 The Market value of circular innovations: the role of collaborations

Circular innovations, characterized by their systemic nature and integration of diverse knowledge sources, are vital for addressing environmental challenges and fostering sustainable economic growth. However, their development is complicated by the absence of standardized solutions and the necessity of integrating heterogeneous technologies and knowledge domains. This study explores how collaboration among firms, universities, and research institutions enhances patent value by leveraging diverse expertise.

In this study, we investigate the (non-linear) effects of knowledge diversity on the market and technological value of patents, using a weighted least squares (WLS) regression model. The indicators adopted are the following.

- **Patent Knowledge Diversity (PKD)** reflects the degree of variation among the patent classification codes in a patent's citations. Wide knowledge search enables inventors to recombine diverse knowledge components, resulting in inventions that span multiple technological domains.
- **Patent Value Dimensions:** Patent value encompasses multiple dimensions, including economic, technological, and legal aspects.
- **Technological Value (TV):** Technological Value reflects the innovative potential of a patent and is often measured by forward citations, which indicate the influence of patented technology on future innovations. However, forward citations are static and may not account for the dynamic evolution of technology. Recent studies propose measuring technological value through metrics like patent technology lifetime (the period between the first and last citation) and technological strength, which combines citation data with patent age. These measures account for the sustained recognition and impact of a patent over time.
- **Market value (MV):** Market Value focuses on the economic worth of a patent, including its potential for revenue generation, strategic importance, and contribution to business objectives such as commercialization, licensing, and mergers.

- **Actor Diversity (AD):** Actor diversity refers to the composition of inventing teams and the geographical distribution of collaborators. By incorporating diverse knowledge inputs and sources, actor diversity significantly impacts the value and success of patenting efforts.

Our econometric findings suggest a dual effects of knowledge diversity. While it broadens the recombination boundary to facilitate technological novelty, it may introduce challenges such as identity ambiguity and misalignment with stakeholder expectations, thereby diminishing economic value. The study also highlights the importance of strategic collaboration among diverse innovative actors to mitigate these complexities and foster value co-creation. By analyzing these dynamics, the research contributes to understanding the interplay between knowledge diversity and patent value, offering insights for optimizing innovation strategies in complex ecosystems.

1.2.6 Regional dynamics of circular innovation

The transition to CE-driven innovation not only hinges on technological capabilities but also on the effective exchange of knowledge, both internally within a firm and externally across regions and borders. This study (Paper 4) examines how intra-regional, inter-regional, and cross-border knowledge networks influence the production of CE-related patents in Europe's NUTS 2 regions, with a specific focus on the semiconductor sector. By analyzing patent data and employing spatial econometric techniques, we aim to investigate the spatial and institutional drivers behind regional disparities in CE innovation performance. We integrate insights from economic geography, which suggests that geographical proximity promotes knowledge transfer, alongside evidence that transregional and transnational networks can compensate for the lack of spatial closeness by facilitating external knowledge flows. Preliminary findings from Italy reveal that 9 out of its 20 regions actively contribute to CE-related innovation, with Veneto, Lombardia, and Emilia-Romagna emerging as key innovators. Distinct technological foci also characterize these pioneering regions. Building on these initial results, we extend our analysis to incorporate a comparative perspective across other European Union member countries, thereby identifying broader patterns and shared challenges. Additionally, the study evaluates the roles of diverse stakeholders—such as firms, research institutions, and policy entities—in driving CE innovation within the semiconductor industry. By highlighting region-specific innovation pathways and uncovering effective knowledge collaboration strategies, this research aims to inform

policymakers and industry leaders on how best to foster sustainable, circular-oriented growth in high-tech sectors.

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1.3 Mapping and evaluating the scaling performance of entrepreneurial ecosystems in CE

1.3.1 Introduction

Innovative startups represent a small but disproportionately impactful segment of the overall firm population, significantly contributing to employment, innovation, and economic growth (Shane, 2009). Consequently, fostering vibrant entrepreneurial ecosystems (EEs) has become a central focus for researchers, policymakers, and practitioners alike (Wurth et al. 2021). EEs are defined as interconnected systems of actors, institutions, and resources that enable the creation and growth of innovative, high-potential startups within specific geographical contexts (Isenberg 2010). However, the evaluation of EEs requires more than a simple tally of startups; it demands an assessment of both their quantity and quality, with a particular focus on their capacity to scale and generate significant economic impact (Guzman and Stern, 2020).

Despite the growing body of research on EEs, little attention has been devoted to evaluating the state of EEs in the context of the Circular Economy (CE). The CE paradigm emphasizes minimizing resource inputs, waste, and energy leakage through strategies like reuse, recycling, remanufacturing, and eco-design (Geissdoerfer et al. 2017). Startups, unburdened by legacy investments and practices, are uniquely positioned to adopt and innovate within CE business models, making them pivotal actors in the transition toward more sustainable economic systems (Henry et al. 2020). While recent studies have explored how knowledge and values related to circularity flow within EEs (Audretsch and Fiedler 2023), systematic frameworks for measuring and mapping CE-focused EEs remain scarce.

This study aims to fill this gap by developing novel approaches to measure and evaluate the state of EEs, with a specific focus on their ability to support CE-related startups. Using a predictive analytics framework, we assess the growth potential of startups based on characteristics observable at their founding, such as intellectual property, board composition, and organizational structure (Andrews et al. 2022). Furthermore, leveraging advancements in Artificial Intelligence (AI), we classify and analyze CE-related startups by extracting and interpreting textual descriptions of their business models. This approach enables a nuanced understanding of how entrepreneurial ecosystems support sustainable innovation.

Our analysis focuses on the Italian context, a country characterized by significant regional disparities in economic performance and entrepreneurial activity. By integrating metrics of quality and quantity of entrepreneurial activity, we provide a comprehensive evaluation of EEs across Italy, with particular attention to the CE domain. This multidimensional assessment not only highlights regional strengths and weaknesses but also offers actionable insights for policymakers seeking to foster sustainable entrepreneurship and reduce regional inequalities.

1.3.2 Literature Review

Over the past two decades, interest from both academic researchers and policymakers in the role of startup companies and in regional economic performance has surged (Feldman 2001; Schrijvers et al. 2024). This growing interest is due to the increasing recognition of the empirical link between startups and regional economic growth (Feldman et al. 2005; Glaeser et al. 2015).

Research on EEs entails a shift in the unit of analysis away from a region's total new venture population or its socio-economy to a more specific type of entrepreneurial activity—productive or growth-oriented entrepreneurship—and the actors and factors affecting this. An EE is defined as a set of interdependent elements, such as informal and formal institutions, networks of entrepreneurs, access to finance, talent, knowledge and support services, coordinated in such a way that they enable growth-oriented entrepreneurship within a particular geographical area (Isenberg 2010).

Despite the popularity of the EE approach in science and policy, there is a scarcity of credible, accurate and comparable metrics of the state of EEs (Leendertse et al. 2022). Evaluating EEs presents indeed significant conceptual and empirical challenges. Key issues include skewness and lagged performance, with a few high-performing startups disproportionately impacting overall economic performance. This makes it essential to measure both the quantity of startups and their growth potential, or "entrepreneurial quality" (Guzman and Stern 2020). Andrews et al. (2020) uses a predictive analytics approach to estimate, for any given startup, the probability of growth of that firm at or near the time of founding (a measure of its quality). Then, leveraging this measure of entrepreneurial "quality" for all firms, they introduce a set of novel entrepreneurship statistics that capture the quantity, quality and performance of any given set of firms, allowing for consistent measures of the state of EE across time and place.

An EE perspective is also useful for better understanding the transition towards a more CE (Kanda et al. 2021). Recent research has started discussing the mechanisms by which circularity can be embedded in EEs through the flow of relevant knowledge and values (Audretsch et al. 2023). Quite notably, it has been argued that startups are in a better position to adopt business models based on CE practices. This is because they do not face sunk costs resulting from legacy investments in old technology, practices and knowledge relevant to a traditional production model in a linear setting (Henry et al. 2020).

1.3.3 Data and Methodology

Quantity and Quality of Startups in a EE

We apply a predictive analytics approach to measure the state of an EE in order to develop indicators that consider both the quantity and quality of startups generated in a EE (Andrews et al. 2022; Guzman and Stern 2020). We use data on the population of Italian innovative startups from the official register website managed by Infocamere (the official repository of the Italian Chambers of Commerce, www.infocamere.it) and collect information on their characteristics at foundation, such as business structure, name features, IPR (patents and trademarks) and board composition using a combination of secondary data sources. We then use a predicting analytics approach in a logistic regression framework to relate the likelihood of exit through IPO/M&A or to reach a minimum size threshold in terms of turnover or assets (€5 million) within 5 years of founding to the type of business structure chosen by the startup (corporation, limited liability company), name features (eponymous firm and name length), intellectual property protection mechanism (patents and trademarks), and board composition (female board member, board experience, serial entrepreneur board member, age of board members). Predicted values are used to assess the startup quality (i.e., the potential scaling performance at a given point of time).

Table 2. Indicators, metrics, and sources.

Indicator	Description	Source
Startup Formation Rate (SFR)	Number of innovative startups at the NUTS3 level.	Infocamere
Entrepreneurial Quality Index (EQI)	Average entrepreneurial quality of startups at the NUTS3 level. Entrepreneurial quality is based on a predictive analytics approach that links the likelihood of exit through IPO/M&A or to reach a minimum size threshold in terms of turnover or assets (€5 Millions) to a set of startup characteristics at foundation (name, trademarks, patents).	Infocamere, ORBIS, Patstat, EUIPO
Regional Entrepreneurship Cohort Potential Index (RECPI)	Overall measure of the state of EE obtained by multiplying SFR with EQI.	Infocamere, ORBIS, Patstat, EUIPO

Identifying CE startups

All indicators are developed by distinguishing startups operating in the CE. Specifically, we exploit an AI-based approach that analyzes the textual descriptions of the value proposition of startups at the incorporation date to identify business models that are consistent with the CE paradigm. Textual descriptions are obtained from Infocamere, the Italian national company business register.

We utilize the natural language understanding capabilities of Open AI GPT models to classify and analyze text based on contextual criteria aligned with the CE paradigm. The AI assistant is provided with a precise definition of CE, following Geissdoerfer et al. (2007), as *a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.*

To operationalize this analysis, we employ a Python script that interacts with the OpenAI API. The assistant is programmed to analyze startup descriptions in Italian, providing concise yet exhaustive assessments in English. Specifically, the model determines whether a startup's value proposition aligns with CE principles and identifies up to three keywords summarizing the startup's primary offering. The script ensures accurate and efficient text processing through the following steps:

1. Text Preprocessing: A cleaning function is applied using regular expressions to remove extraneous characters, standardize text, and prepare it for analysis.
2. API Interaction: The assistant processes each startup's description, returning structured outputs that confirm whether the business is consistent with CE and generate relevant keywords.
3. Response Parsing: A custom function extracts key components (circular classification and keywords) from the assistant's response for further analysis.
4. Data Export: The results, including the startup's unique identifier, CE classification, and keywords, are saved in a structured format.

The wordcloud depicted in Figure 1 highlights the keywords extracted from the business descriptions of startups classified as CE-related by the AI model. These keywords represent core CE concepts and industries closely associated with the CE paradigm, such as recycling, sustainability, waste management, renewable energy, and eco-design. Table 2 reports the distribution of startups and CE-related startups across time.

[illegible]

Year	N. of startups	N. of CE-related startups	Ratio
2015	1,988	569	0.29
2016	2,186	639	0.29
2017	2,785	789	0.28
2018	2,329	655	0.28
2019	2,445	766	0.31
2020	2,966	920	0.31
2021	2,973	986	0.33
Total	17,672	5,324	0.30

Figure 2 illustrates the Startup Formation Rate (SFR) and its breakdown in relation to CE startups. The left panel displays the overall SFR, which measures the number of innovative startups at the NUTS3 level across Italian regions. This serves as an indicator of entrepreneurial activity within the ecosystem. The

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center panel focuses specifically on startups operating in in CE. The right panel shows the proportion of CE startups relative to the total SFR. This share reflects the extent to which CE startups contribute to the overall entrepreneurial ecosystem within the regions analyzed. The highest concentration of startups appears in metropolitan regions such as Milan and Rome, while Southern regions show a lower density. Regions in Northern and Central Italy, such as Lombardy, Emilia-Romagna, and Tuscany, also exhibit a strong presence of CE startups. Unlike the first two panels, Southern regions, such as Sicily and Calabria, demonstrate a higher share of CE startups relative to the total SFR. This suggests that, while entrepreneurial activity is less dense in these regions, a larger portion of their startups are CE-focused. Northern regions such as Lombardy, despite their high absolute numbers, display a lower percentage share, likely due to their larger overall entrepreneurial base.

Figure 3 provides a detailed view of the Entrepreneurial Quality Index (EQI) across Italian regions, highlighting general EQI, EQI specific to the CE, and the ratio of CE-related EQI to overall EQI. Northern regions, such as Lombardy and Emilia-Romagna, demonstrate the highest EQI, consistent with their strong entrepreneurial ecosystems. However, some Southern regions display a relatively stronger CE-EQI compared to their overall EQI, highlighting the presence of high-quality CE startups despite the lower overall entrepreneurial activity.

Finally, Figure 4 illustrates the Regional Entrepreneurship Cohort Potential Index (RECPI) across Italian regions. Northern regions and largest metropolitan areas display the highest RECPI values, reflecting robust entrepreneurial ecosystems with strong startup density and quality, while Southern regions, like Calabria, Sardinia and Sicily, lag behind in overall RECPI. Quite interestingly, some Southern regions exhibit moderate RECPI in CE, indicating a notable presence of high-quality CE startups. The proportion of RECPI in CE to overall RECPI is highest in Southern regions, where CE startups constitute a significant share of the entrepreneurial potential, contrasting with Northern regions where broader entrepreneurial activity dilutes CE-specific contributions. These patterns suggest opportunities for targeted policies to support CE-oriented entrepreneurship in the South, addressing regional disparities and fostering sustainable innovation.

Figure 2. Startup Formation Rate: Overall SFR (left), SFR in CE (center), and Share of SFR in CE on Overall SFR

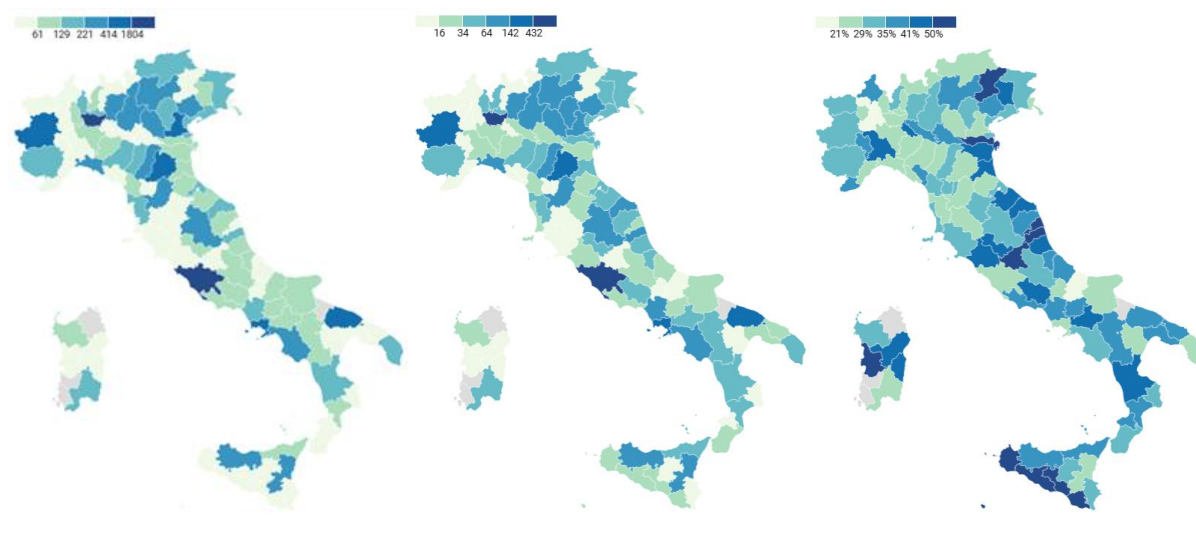


Figure 3. Entrepreneurial Quality Index: Overall EQI (left), EQI in CE (center), and Ratio of EQI in CE on Overall EQI

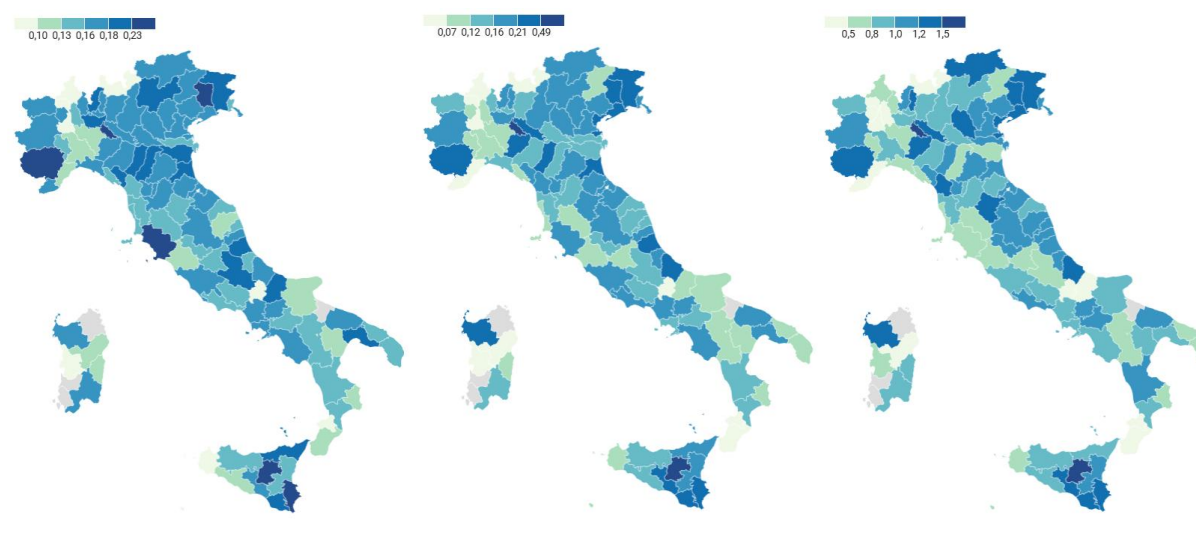
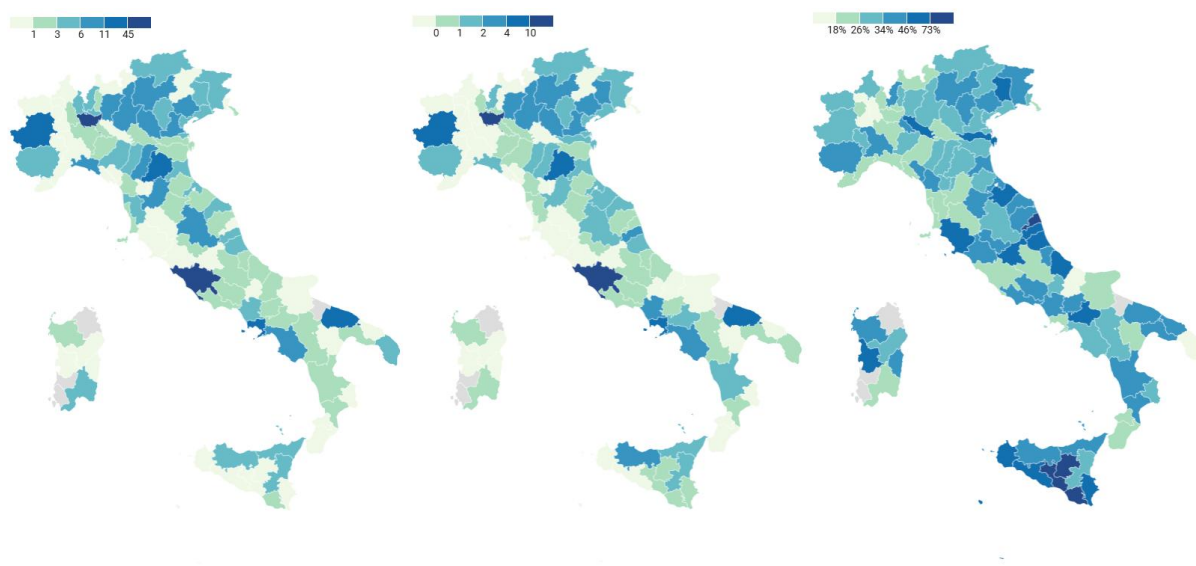


Figure 4. Regional Entrepreneurship Cohort Potential Index: Overall RECPI (left), RECPI in CE (center), and Share of RECPI in CE on Overall RECPI



1.3.5 Conclusion

This study offers valuable insights into the measurement and evaluation of EEs, with a specific focus on the CE. By combining traditional metrics with innovative predictive analytics and AI, we have developed a comprehensive framework for assessing both the quantity and quality of startups within EEs, while also highlighting the role of CE-focused startups. Our findings suggest that while Northern Italian regions demonstrate strong overall startup activity and higher quality startups, Southern regions, despite their lower overall entrepreneurial density, show a notable presence of high-quality CE startups. This highlights the potential for CE-driven entrepreneurship to be a catalyst for sustainable development, particularly in regions with fewer traditional startups.

Policymakers can leverage these insights to target interventions that support the scaling of CE startups, particularly in underperforming regions where EEs could benefit from greater alignment with sustainable practices. Our study also demonstrates the value of utilizing advanced AI tools for classifying and analyzing the business models of startups, offering a novel approach to understanding how startups contribute to the transition towards a CE. By focusing on regions with the highest potential for CE growth, policymakers can foster sustainable business practices that will contribute to long-term economic resilience and environmental sustainability.

Future research could further explore the ecosystem-level factors that stimulate the emergence and development of CE EEs. While this study focuses on the role of startups and their potential for scaling, a deeper examination of the broader institutional, policy, and market dynamics that support or hinder CE-oriented entrepreneurship would provide valuable insights. For example, understanding how specific regional policies, access to finance, or the availability of CE-related knowledge networks influence the success of CE-related startups could enhance the development of targeted interventions. Additionally, investigating the role of corporate partnerships, supply chain dynamics, and consumer behavior in fostering a more circular business environment could shed light on the mechanisms that enable the scaling of CE startups. Longitudinal studies that track the evolution of CE EEs over time would help to identify the key drivers and barriers to the sustainable growth of CE startups. Finally, expanding the analysis to other geographical contexts with varying levels of CE adoption could provide comparative insights into how different EEs evolve and the specific conditions that foster or inhibit the growth of CE-oriented ventures.

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1.4 University and CE performance

1.4.1 Circular Economy report

The purpose of the Circular Economy (CE) Score indicator in higher education is to evaluate the contribution of tertiary education to the transition towards a circular economy. Despite the crucial role of Higher Education Institutions (HEIs) in society and in facilitating transitions, the implementation of CE within HEIs remains an emerging topic, with limited information available on the practical application of CE strategies in this context (Mendoza et al., 2019a). In addition, few studies have analyzed the implementation and the evaluation of circularity principles adopted and no methodologies or tools have been developed to measure the level of CE implementation in HEIs (Mendoza et al., 2019b; Valls-Val et al., 2023)

The aim of our study is, first, to identify potential indicators for measuring the circularity of universities. However, in light of the ongoing debate on rankings in the higher education sector (Marginson & Van Der Wende, 2007) and particularly the recent introduction of sustainability rankings (Kaiser et al., 2022), we seek also to explore how rankings represent and impact circular economy indicators. Specifically, we seek to determine whether the indicators included in these rankings, which primarily pertain to the broader concept of sustainability, can also effectively capture the Circular Economy orientation of various institutions. Additionally, it is worth investigating whether universities that actively prioritize sustainable development are equally equipped to contribute to CE initiatives, thereby bridging these two interconnected paradigms.

Universities can contribute to the circular economy by considering their triple missions: teaching, research, and outreach. In light of the previous considerations, the objective of our indicator is to assess the circularity propensity of universities with regard to their teaching and research activities. This indicator will account for various elements, including courses, publications, citations, and research centers that are associated with the circular economy. Data will be collected from online databases and websites in order to ensure verifiability and reproducibility. The formulation of a metric to assess the engagement of HEIs in the transition towards a circular economy presents a multifaceted challenge, given the absence of a predefined model. Deda et al., (2022), Serrano-Bedia & Perez-Perez, (2022) and the Ellen MacArthur Foundation, (2013), posit that HEIs can contribute to the transition towards a circular economy in five distinct categories: by incorporating CE principles into their teaching,

by guiding student-led innovation, by encouraging research on CE, by shaping and influencing local change, and by managing their campuses in a sustainable manner. The first and third categories are particularly significant for our purpose, as they closely align with the teaching and research missions of universities.

Despite its potential contributions, the specific indicator under consideration has not yet been implemented or utilized for research purposes. Instead, a similar study has been conducted with a broader focus on general sustainability indicators. The approach and key findings of this analysis are presented below.

1.4.2 Extended approach

To introduce the extended approach, we begin by outlining the rationale that underpins the selection of this topic, highlighting its significance and relevance within the field. Following this, we present the key results derived from the study and discuss their broader implications. Finally, we explore a potential application of this research framework to the context of the circular economy, suggesting ways in which it could provide valuable insights and contribute to further advancements in this area.

Sustainable development represents one of the most significant challenges currently facing society, and education has been recognized as a crucial element in addressing this issue (Lozano et al., 2015; Rau et al., 2018; UNESCO, 2024). In light of the societal push toward sustainability and the expected contribution of HEIs, new rankings have emerged (Gutiérrez-Mijares et al., 2023; Suwartha & Sari, 2013), affecting the ongoing debate about rankings in the higher education sector (Marginson & Van Der Wende, 2007).

Similar to the concerns surrounding traditional rankings, sustainability ones also faced criticism regarding their validity and reliability in measuring the quality of higher education (Lauder et al., 2015; Saisana et al., 2011). Moreover, the multifaceted nature of sustainability makes it even more challenging to assess (Böhringer & Jochem, 2007; Hoover & Harder, 2015; Van Kerkhoff, 2014). Despite the extensive literature on rankings, sustainability rankings are more recent and less studied. Some researchers address the assessment issue through the qualitative analysis of indicators (Bautista-Puig et al., 2022; Galleli et al., 2022; Suwartha & Sari, 2013) while other studies evaluate sustainability ranking with the goal of proposing new indicators and methodologies (Karasan et al., 2023; Lukman et al., 2010). However, even if numerous research has been conducted on the impact of traditional rankings on university performance (Baltaru, 2019; Katsumoto et al., 2024; Meredith, 2004), research focusing on the effect of sustainability ranking is limited (Atici et al., 2021; De La Poza et al., 2021; Sierra-García et al., 2024).

Despite their criticism and new proposals for evaluating universities, rankings are and will remain pervasive in the higher education sector, posing the importance of studying both their validity and impact (Olcay & Bulu, 2017). Furthermore, the topic of sustainability has recently gained significant attention, and universities are expected to make contributions to this area (Žalėnienė & Pereira, 2021). Therefore, it becomes crucial to investigate how sustainability performance is influenced by or reflected in university rankings. In light of these considerations and given the importance of the aforementioned topics, our study aims to address these gaps by providing new empirical evidence. The objective of this study is to empirically assess the nature of the relationship between sustainability ranking metrics and university sustainability performance. Following the idea that rankings are used to reduce information asymmetry (Rindova et al., 2018) a first direction of causality from performance to rankings has been introduced. We hypothesize that if rankings can act as a signal of university quality, they must be able to highlight an improvement in performance. Otherwise, we can accept the criticism concerning data validity and reliability on reputation rather than quality (Marginson & Van Der Wende, 2007).

On the other hand, following the stream of research about the ranking impact (Clementino & Perkins, 2021) it is possible to introduce the opposite causality direction: from ranking to performance. We therefore hypothesize that rankings not only are influenced by performance but also influence it (Fowles et al., 2016). As a result, a higher ranking position may lead to improved sustainability performance. In this case, universities might respond to direct incentives by focusing on the specific performance metrics included in rankings, thereby boosting their scores (Espeland & Sauder, 2007). Otherwise, rankings may be able to raise awareness within the organizations and act as a real driver of change. In this case, sustainability rankings may impact on all the sustainability performance within the organizations. Lastly, we do not exclude that both relationships exist, indeed it is possible that the two phenomena are self-sustaining.

Methodology and Results

To identify the nature of the relationship, data were collected from 75 Italian HEIs between 2010 and 2023. Italy represents an exemplary setting for this study due to the early inclusion of its universities in the ranking and the government's push towards sustainability. We use the UI GreenMetric as a sustainability ranking to test the relationship. In considering sustainability performance, data takes into account the multivariate nature of sustainability and the different university missions. For each institution, we gather data on their academic programs, research initiatives, and

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engagement in the third mission that can be related to sustainability. Differently from the approach on just circular economy here we consider all the three university missions for a broader approach. In this case the number of courses, publications, and spinoffs are included in the GreenMetric final score, while the other variables are not. Lastly, we consider a set of control variables such as the number of students, academic personnel, tuition fees and participation in THE ranking to better isolate the effect of the independent variables. The data were collected directly from online sources, ensuring verifiability. Subsequently, the Granger test was employed to evaluate the direction of causality. This test allows us to determine the causal relationship between the GreenMetric ranking and the sustainability performance of universities.

Our results provide empirical evidence that a causal relationship exists in both directions. The results indicate that the ranking is sensitive to the change in the number of courses, publications, and in the number of green patents while there is no evidence for the number of citations and sustainability spinoffs. Regarding control variables, inclusion in the THE ranking seems to have a positive impact on the ranking position. This suggests that the universities included in the ranking may be of higher quality or have more experience with the ranking process and dedicated staff.

These results indicate that an enhancement in sustainability performance is associated with an improvement in ranking position. Improvements in both the education and research missions are reflected in the ranking score. Specifically, our results seem to indicate that sustainability rankings are very sensitive to the number of publications, mirroring the behavior of traditional rankings (Vernon et al., 2018). Lastly, it can be noted that innovations have also a great impact on GreenMetric, even though the number of patent applications is not included in the data collected to be ranked in the GM. In contrast, a change in citations and spinoffs is not highlighted by the ranking. The lack of empirical evidence regarding spinoffs can be attributed to the inherent challenges in measuring sustainable spinoffs in comparison to green patents, which are defined by a precise code for identification. In conclusion, as might be expected, the variables included in the ranking measures themselves have the greatest causal effect on the ranking score. However, it is evident that patents exert a considerable influence on the ranking, suggesting that universities with a significant number of green patents are likely to demonstrate a general sensitivity to sustainability issues.

On the other hand, we consider the causal effect of ranking on sustainability performance. Ranking has a positive impact on the number of courses and publications. On the contrary, the model outlines a negative impact of rankings on

citations and patents applications. There is no statistical evidence on the number of spinoffs. Lastly, the results demonstrate that the control variables exert no significant influence on the outcomes, except for the year dummies. These findings confirm that rankings can prompt organizations to take reactive measures to improve their performance in the areas included in the ranking itself, especially when the measures are simple (Espeland & Sauder, 2007). Combined with the previous results this suggests also that ranked universities are very sensitive to the education and research areas in terms of sustainability.

In contrast, the impact of rankings on citations and patents indicates that a higher ranking position leads to a reduction in sustainability performance not included in the ranking itself. In particular, with regard to research output, being ranked has been found to increase the quantity of publications, but not the quality. This is demonstrated by the negative effect that ranking has on the number of citations. Similarly, being ranked has a negative impact on the third mission measure, which is not included in the ranking and therefore more challenging to improve. Combined with previous results, it appears that a high level of performance in relation to the third mission is conducive to an enhanced ranking. This is likely due to the fact that universities are capable of significantly improving their performance in conjunction with patents. Otherwise, once a ranking has been achieved, the importance attached to the patent measure is diminished, as the focus shifts toward measures that are collected by the ranking itself.

The results demonstrate that GreenMetric is sensitive to changes in sustainability performance, suggesting that, in general, rankings can highlight improvements in performance. As expected, the empirical tests revealed that the variables included in the data collected by the ranking questionnaire are those with the highest impact. This assessment shows that the data provided by the universities has been verified and that the rankings are not based solely on reputation. Concurrently, and most importantly, the results show that GreenMetric ranking has an impact on the sustainability performance of universities. Our findings provide empirical evidence of the reactive behavior of Italian universities. This research demonstrates that even if institutions are skeptical about rankings, they still respond to them (Espeland & Sauder, 2007). The results indicate that the GM ranking positively affects the variables included in the ranking measure, while it has a negative effect on the others. These findings support the theory of reactivity: universities seek to align themselves with top-ranked institutions due to their perceived status as the "best" (Clementino & Perkins, 2021). At the same time, institutions may neglect other indicators in their efforts to improve their scores included in the GM assessment. Given the predominance of university rankings and their constant use despite inherent

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weaknesses, it is clear that universities do not merely subject themselves to external evaluations; instead, they interpret and manipulate rankings (O'Connell & Saunders, 2013). The variables associated with the research outcomes clearly illustrate this situation, as universities probably encourage researchers to increase the number of publications, even at the expense of quality.

Dicussion and conclusions

Demonstrating the causal relationship between sustainability ranking and sustainability performance could hold valuable implications for university managers, policymakers, and future studies in this field. University managers may consider rankings as a form of feedback or an external source of pressure (Rindova et al., 2018). In general, organizations perceive a favorable ranking position as an indication of a credible third-party assessment that can influence stakeholder perceptions (Callery, 2023). As a consequence, managerial decisions may be driven by the objective of attaining strategic goals (O'Connell & Saunders, 2013) or by the pursuit of change based on the rankings in question (Locke, 2014). Our results can be valuable in showing managers the consequences of being included in a ranking such as GreenMetric, and in providing a general overview of how rankings work. On the one hand, managers strive to maintain their position in the ranking (Vidal & Ferreira, 2020), and understanding the causal relationship can serve this purpose. Concurrently, given the recent focus on performance measurement in the public sector (Lynch, 2015), understanding the causal relationship between sustainability performance and ranking can be helpful in designing proper strategies. At the same time, this research shows that rankings can be biased, and a university may decide not to take part.

Considering the policymakers, they frequently use university rankings as a proxy of their performance to supply a lack of information (Dill & Soo, 2005). Since governments are key stakeholders for HEIs, these rankings can significantly influence funding allocation and grant distribution (Hazelkorn, 2014). This research can shed light on the true sensitivity of rankings to actual performance. This research confirms empirically that if stakeholders and policymakers use rankings as a basis for their choices may result in sub-optimal decisions (Saisana et al., 2011). In addition, if policymakers use university rankings to set grants, they may give an incentive to universities to manipulate the ranking rather than to be more sustainable. Basing decisions on ranking can also encourage conformity among institutions. Beyond policymakers, this research can also prove beneficial to other stakeholders. Despite the value placed on rankings for their ability to synthesize information, this study

demonstrates that the data presented in such rankings does not necessarily reflect reality. Conversely, institutions that appear to be more sustainable may, in fact, be merely engaging in the practice of ranking-driven competition.

Lastly, our findings can contribute to the extant literature because they represent the first empirical observation of the causal relationships between the sustainability ranking and the sustainability performance within universities. To the best of our knowledge, only Atici et al., (2021) and De La Poza et al., (2021) studied the impact of sustainability rankings on academic performance, while (Sierra-García et al., 2024) identified the contribution of university quality to sustainable rankings. In this sense, our research can contribute on one hand to the stream of knowledge relative to rankings and their impact on HEIs, recommending checking and eventually including this double relationship in future studies. In addition, we hope to trigger a discussion also about sustainability performance and their assessment.

The study acknowledges its potential contribution to the field but highlights several limitations and future possibilities. It notes that online-retrieved data, while verifiable, may overlook important university features. The introduction of official shared metrics could enhance comparability. The study uses indicator-based measures for evaluation, although alternative approaches like accounts and narrative assessments exist and could be explored further. It employs the GreenMetric ranking, acknowledging that different indicators may vary in effectiveness. Future research could gather more data from other sustainability rankings to validate findings. Lastly, the study is limited to a single country, suggesting potential for future research to broaden its scope.

Our objective is to examine and adapt this extended approach to evaluating circular economy performance. In this context, certain distinctions emerge. Firstly, the inclusion of specific CE indicators, particularly in the domains of teaching and research, represents a significant advancement for the existing body of literature. Secondly, as these indicators are not yet incorporated into existing rankings, this research does not establish causal relationships but rather provides an initial exploration of how CE is represented within these frameworks. The limitations identified in the broader study are also applicable to research on CE. However, considering that CE is a more narrowly focused topic compared to general sustainability, it may prove beneficial to explore alternative methods of data collection and to investigate other ranking systems. This could help identify and better understand potential relationships and trends within the context of circular economy.

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1.5 Mapping scientific and technological efforts for CE research in Italy

1.5.1 Mapping Technological efforts

The circular economy (CE) paradigm has recently gained increasing attention in both academic and policy circles. Existing literature has stressed that the transition to the CE paradigm implies innovation aiming to change consumption and production behaviors and technologies. Empirical studies have focused on the drivers and effects of the adoption and generation of CE innovations, based on survey and patent data, respectively. However, identifying and tracking CE innovations through patents has been challenging due to the lack of a domain specific classification system. Existing methods are often insufficient to capture the diversity and complexity of CE technologies. This chapter maps CE innovation efforts using a novel methodology for the identification and classification of CE-related patents, combining large language models (LLMs), pre-trained language models (PLMs), and topic modelling techniques. By applying these methodologies to patent data, we uncover significant trends in the distribution of CE patents in sectors, technological fields, and geographical regions. Our exploratory findings highlight a growing cross-sector engagement with CE principles, underscoring the transformative potential of circular economy innovations in driving sustainable industrial practices.

1.5.1.1 Results

The developed methodology is described in [D.5.1.1](#) and it is based on the joint implementation of LLM and BERT algorithm to process patents' abstracts. It allowed us to identify 864,714 European patent families as CE-related. Table 1 and 2 provide two examples of improvement with respect to the keyword retrieval approach and to the CPC codes. Table 1 displays the example of a patent that would have not been included while using the keyword retrieval approach – since it does not make any specific reference to the CE and neither to one of the usually correlated terms as “recycle” –, but that was identified when using the methodology proposed. Table 2, on the other hand, highlights two types of misclassifications when relying solely on CPC/IPC codes. The first example is a CE-related patent – it describes kitchen garbage treatment equipment, thus promoting biodegradation and efficient waste

processing – and would be overlooked using the Y02W code. The second example instead is a patent classified as Y02W but not directly related to CE, as it describes a method and composition to reduce the emission of methane and carbon dioxide from farm fertilizers during storage. Although environmentally beneficial, this invention focuses on the mitigation of climate change rather than CE.

CE-patent not mentioning keywords
Methods and systems are provided for mapping the distribution of residue material in an environment in which one or more agricultural machines are operable. A sensing arrangement comprising one or more sensors mounted or otherwise coupled to an agricultural machine operating within the environment is used to obtain sensor data indicative of residue material [...].

Table 3. Improvement with respect to the keyword retrieval approach.

CE patent not Y02W	Y02W patent not CE
The invention discloses kitchen garbage treatment equipment based on biodegradation, the equipment comprises a filtering mechanism, a stirring mechanism, a crushing mechanism and a fermentation mechanism, the filtering mechanism is connected with the crushing mechanism and the stirring mechanism, and the fermentation mechanism is arranged in the crushing mechanism and the stirring mechanism; [...].	The present invention relates to a method and to the use of a composition, each for reducing the emission of the environmentally harmful climate gases methane and/or carbon dioxide from farm fertilizers while they are being stored.

Table 4. Improvement with respect to the CPC code Y02W.

When looking at the distribution of CE patents across the 5R, it is possible to observe a predominance of patents related to the categories "Reuse" and "Recycle", respectively, 29.7% and 26.2% of the total dataset (Figure 1). In third place there is the topic "Reuse" (20.0%), followed by "Recycle" (15.91%), and "Refurbish" (8.2%).

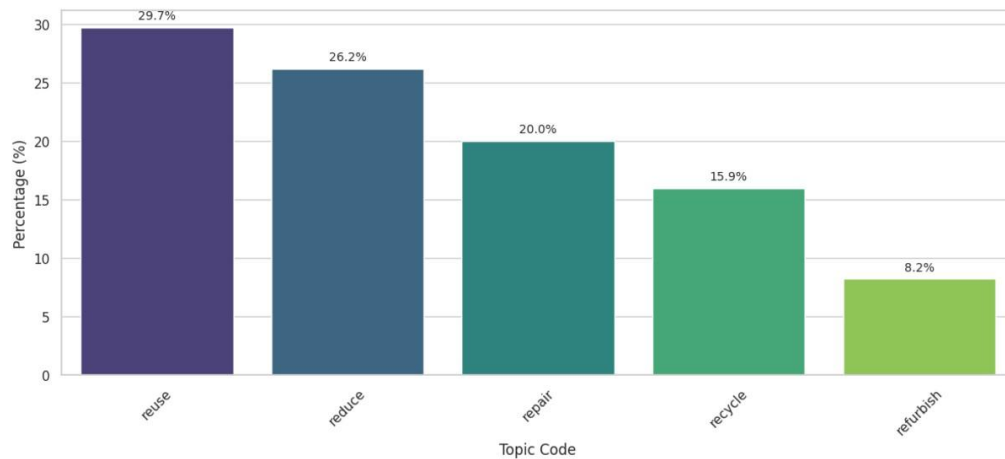


Figure 7. Distribution by 5R topics.

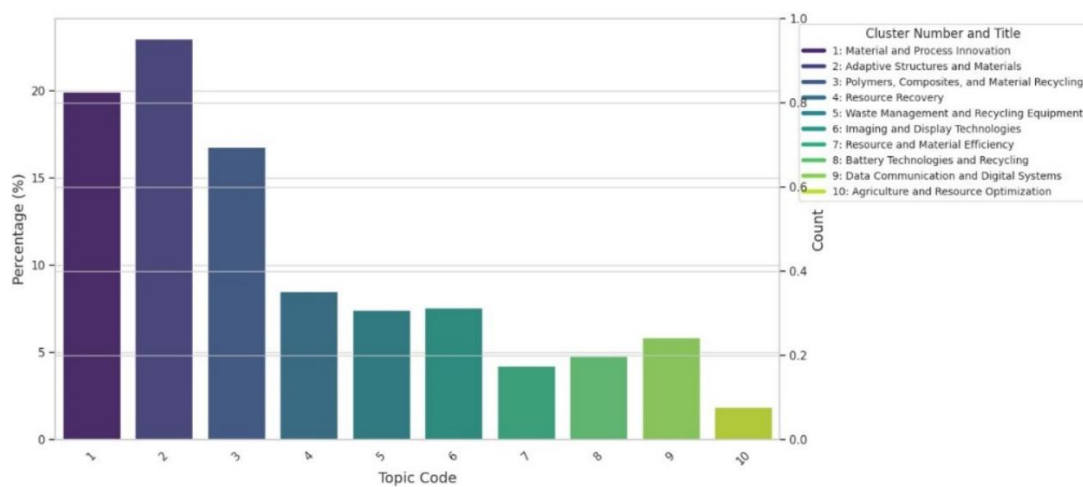


Figure 8. Distribution by 10 CE topics

Looking instead at the 10 CE topics, we can observe their distribution in Figure 2 (Table A1.). The topic concerning "Adaptive structures and materials" is the most common topic across patents, collecting 23.07% of the whole dataset. Almost 20% of the patents concern "Material and process innovation", while 16.8% "Polymers, composites, and material recycling". Moving on, there is a noticeable jump in terms of topic size, as the next one covers 8.5% of patents and it is related to "Resource efficiency and water treatment", 7.5% both to "Imaging and display technologies" and "Waste management and recycling equipment", and 5.8% to "Data communication and digital systems". Finally, 4.81% of the patents refer to "Battery technologies and recycling", 4.2% "Resource and material efficiency", and 1.9% "Agriculture and resource optimization".

Table A2. provides examples for each of these topics. Examples for the topic "Material and process innovation" are a technology for purifying a fibrous suspension that

might facilitate the recycling or reuse of materials, a recyclable laminated polyolefin-based film structure, and a dynamic watering plan optimizing resource use by adjusting irrigation schedules, reflecting a focus on improving processes for resource conservation. For what concern the "Adaptive structures and materials" topic, an example is a solar panel cleaning system that introduces flexible, wind-displaceable elements that improve the cleaning efficiency of solar panels and potentially maximize the life of the solar panel themselves. A fiber-reinforced resin molding method able at improving the strength and thus the durability of the materials and an upcycling process for polymers are examples for the "Adaptive structures and materials" topic. In the category of "Resource recovery", a reusable blister package assembly promotes packaging reuse, thus supporting the reduction of single-use plastics, while the semiconductor repair circuit facilitates the repair of the apparatus. A patent concerning systems and methods for detecting a waste receptacle is classified as related to "Waste management and recycling equipment", while for "Imaging and display technologies", an example is given by a bifacial solar module capable of maximizing the amount of light captured using reflective materials, allowing the end to improve solar energy efficiency. "Resource and material efficiency" is exemplified by a system for generating energy from train disc brakes and a building material with plant-based reinforcement. A secondary battery innovation and a process for recovering metals from batteries exemplify the topic on "Battery recovery and recycling", while in "Data communication and digital systems", a system for calculating carbon footprints leverages digital tools to track environmental impact and incentivize sustainable behaviors. Finally, the category "Agriculture and resource optimization" includes an optimized irrigation method and a real-time crop yield prediction system to estimate yields and optimize farming practices.

The following paragraphs provide a comprehensive mapping of the classified datasets. The analysis provides insight into the temporal patterns of CE innovation, its geographical distribution and sectorial activity, incorporating data on CPC classes, NACE2 codes, and technology classifications. For each dimension, the analysis is conducted both at an aggregated level and by differentiated between the 5R principles and the 10 CE topics. This multifaceted approach ensures a thorough understanding of the dynamics that drive CE innovation.

1.5.1.2 Annual trend

Between 1990 and 2019, the trajectory of CE patents largely mirrors the overall growth trend, but exhibits a significantly steeper upward trend beginning in the early 2000s (Figure 3). Compared to Y02W patents, CE patents demonstrate both a faster growth and a higher overall magnitude. This pattern holds across the 5R topics (Figure A.1), with significant increases observed for “Reduce” and “Reuse” patents in the late 1990s. A distinct rise in “Repair” patents becomes evident starting in 2007, while growth in “Recycle” patents appears to plateau and converge from 2010 onwards. Figure A.2 differentiates the trend in the ten CE topics previously described. Overall, the topic “Material and process innovation” and “Adaptive structures and materials” consistently shows the highest counts throughout the period, peaking around 2010 and exhibiting slight fluctuations thereafter. Other topics like “Polymers, composites, and material recycling” show a steady upward trend, stabilizing in the later years, while “Resource recovery”, “Battery technologies and recycling”, and “Resource and material efficiency” exhibit moderate but consistent growth.

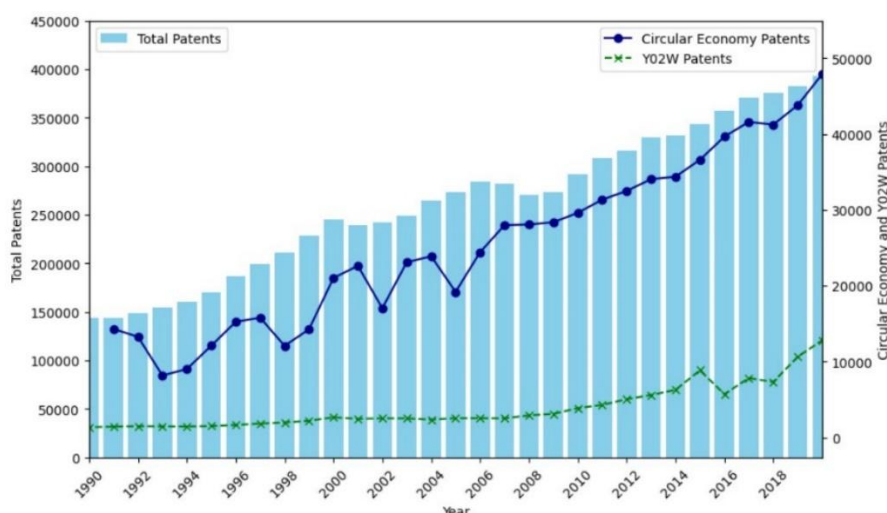


Figure 9. Annual trend CE patents.

1.5.1.3 Geographical Mapping

At a spatial level, CE patent activity shows a marked concentration in key innovation hubs throughout Europe, as shown in Figure 4 (the top 10 Nuts 3 areas are listed in Table A.3). Main-Kinzig-Kreis, in Germany (5,382 patents, 2.08%), Paris, in France (4,060 patents, 1.57%) and Helsinki, in Finland (3,179 patents, 1.23%) lead the rankings. Other industrial centers, such as Hauts-de-Seine, Zurich, and Milan, also show

significant activity. When analyzed according to 5R topics, the distribution of CE patents reveals nuanced regional strengths (Table A.4). Regions such as Main-Kinzig-Kreis, in Germany, excel in "Reduce" (1.90%) and "Repair" (1.61%) innovations, while Paris leads in both "Reuse" (1.67%) and "Refurbish" (1.53%). Milan, Zurich, and Copenhagen show strong, balanced contributions across multiple Rs, reflecting their diverse industrial and technological bases. Further analysis of the 10 CE topics further enriches this geographical mapping in Figure A.3 (Table A.5). Main-Kinzig-Kreis stands still out across multiple CE topics, with a notable focus on "Data Communication and Digital Systems" (4.31%), "Material and Process Innovation" (2.11%) and "Adaptive Structures and Materials" (2.32%). Paris, in contrast, shows a more diversified profile, leading in categories like "Resource and Material Efficiency" (1.92%) and "Resource Recovery" (1.86%), which reflects its advanced infrastructure and role in digital transformation. Copenhagen performs well in topics such as "Polymers, composites, and material recycling" (2.55%), while Freiburg is recognized for its strengths in "Recycling equipment and waste management" (2.08%).

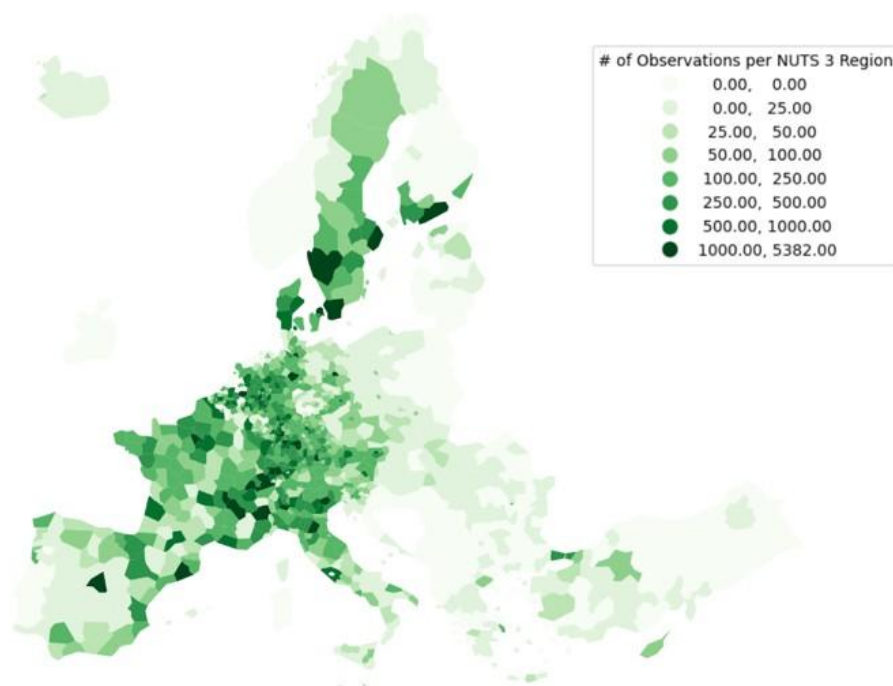


Figure 10. Distribution of CE patents at NUTS3 level.

1.5.1.4 Distribution by CPC codes

At the aggregate level, the technological classifications reveal a strong focus on class B32B for layered products (38.68%), H01M focuses on processes or means for

the direct conversion of chemical energy into electrical energy, for example batteries (35.64%), B29C on the shaping or joining of plastics (23.36%), as can be observed in Table 3. In terms of technological focus according to 5R principles (Table A.6), "Reduce" emphasizes energy and material efficiency, with processes such as H01M (processes or means, e.g. batteries, 5.80%) and B01D (separation, 4.27%) leading. "Reuse" is dominated by layered products (B32B, 5.59%) and plastic shaping technologies (B29C, 4.94%). "Recycle" highlights innovations in plastic reprocessing (B29C, 7.37%) and waste management (Y02W, 3.59%). "Repair" technologies have a strong presence in batteries and water treatment, while "Refurbish" emphasizes layered materials and structural enhancements in building and manufacturing. The 10 CE topics illustrate a nuanced distribution of patents in various technological domains (Table A.7). "Material and process innovation" is a major factor in container technology (B65D, 5.66%) and semiconductor devices (H01L, 5.21%). Similarly, "Adaptive structures and materials" is characterized by a strong presence of plastic shaping technologies (B29C, 6.29%) and layered products (B32B 5.61%). Also in "Polymers, composites, and material recycling," layered products and plastic technologies (B32B, 10.29%; B29B, 7.29%) are dominant, illustrating a focus on high-tech materials essential for recycling and reuse. For "Resource recovery", treatment of water (C02F, 10.32%) and separation (B01D, 9.46%) lead, highlighting the integration of advanced materials in the management of environmental resources.

Code	Title	n. patents	% patents
B32B	Layered products	106,388	38.68%
H01M	Processes or means	104,98	38.17%
B29C	Shaping or joining of plastics	96,691	35.16%
C02F	Treatment of water, waste water, sewage, or sludge	75,929	27.61%
H01L	Semiconductor devices not covered by class H10	63,859	23.22%
Y10T	Technical subjects covered by former US classification	59,281	21.56%
B01D	Separation	57,754	21.00%
B65D	Containers for storage or transport of articles or materials	57,551	20.93%
C04B	Lime, magnesia; slag; cements; compositions thereof	47,15	17.14%
Y02E	Reduction of greenhouse gas (GHG) emissions, related to energy generation, transmission or distribution	39,573	14.39%

Table 5. Distribution of CE patents across CPC codes.

1.5.1.5 Sectorial distribution

Industries identified through the NACE classification display a broad engagement with CE (Table 4). The manufacture of basic chemicals dominates (16.79%), while other sectors such as special purpose machinery (10.28%) and rubber and plastic products (6.94%) also show significant contributions, underscoring the diverse applicability of circular economy approaches in industrial domains. Sectorial diversification expands further when we look at differences between the 5R categories (Table A.8). For "Reduce," the chemical and pharmaceutical industries dominate, while "Reuse" shows strong engagement from rubber and plastic manufacturing (5.22%), and "Recycle" is led by machinery and motor vehicle manufacturing. The 10 CE topics insights presented in Table A.9 further delineate the sectoral contributions. For "Material and process innovation", the manufacture of other special-purpose technologies (8.78%) plays a significant role, while "Data Communication and Digital Systems" sees a robust presence of computers manufacturing (15.54%). "Agriculture and Resource Optimization" stands out for the dominance of basic chemicals (20.90%), pharmaceuticals (16.54%), and food preparations (9.44%). Across all topics, the assigned NACE codes appear to align well with the corresponding CE dimensions, reflecting the sectoral relevance to each area of circular economy innovation.

Code	Name	n. patents	% patents
20.10	Manufacture of basic chemicals	46,185	16.79%
28.90	Manufacture of other special-purpose machinery	28,296	10.28%
22.00	Manufacture of rubber and plastic products	19,109	6.94%
26.10	Manufacture of electronic components and boards	17,489	6.35%
21.00	Manufacture of basic pharmaceutical products	15,84	5.75%
28.29	Manufacture of other general-purpose machinery n.e.c.	15,623	5.68%

26.30	Manufacture of communication equipment	13,914	5.05%
27.20	Manufacture of batteries and accumulators	13,242	4.81%
26.20	Manufacture of computers and peripheral equipment	12,795	4.65%
28.10	Manufacture of general-purpose machinery	12,639	4.59%

Table 6. Distribution of CE patents across NACE codes.

1.5.1.6 Technical fields

At the aggregate level, the largest share is held by "Other special machines", accounting for 13.3% of total patents (Table 5). This category encompasses a wide variety of specialized machinery, reflecting the broad scope of innovation in manufacturing and industrial technologies. The following closely are "Electrical machinery, apparatus, and energy", (10.3%), and "Chemical engineering" (8.8%). The fields of "Electronic components and boards manufacturing" (8.6%) and Handling (8.2%) also contribute significantly, demonstrating the importance of advanced manufacturing, logistics, and automation technologies in the wider technological landscape. When examining the distribution of patents across the 5R topics in table A.10, the "Reduce" one is dominated by "Electrical machinery, apparatus, energy" (7.93%), followed by "Chemical engineering" (7.16%) and "Other special machines" (6.56%). The Reuse category sees a clear dominance of "Other special machines" (10.14%) and "Manufacture of electronic components and boards" (5.62%), while patents under the "Recycle" category are heavily concentrated in "Other special machines" (8.86%), followed by "Transport" (7.54%) and "Mechanical elements" (6.48%), while "Handling" stands out as the most patent-intensive field in the "Repair" category, with 17.65% patents. At a more granular level, when examining the 10 CE topic distribution in Table A.11 of patents across specific topics, in the category "Material and Process Innovation", "Handling" (10.70%) leads the charge. "Other special machines" (7.44%) and "Chemical engineering" (7.10%) also play an important role. Patents in the "Imaging and Display Technologies" category show a focus on "Optics" (17.82%), while the "Resource recovery" category sees strong contributions from "Environmental technologies" (15.21%).

Tech. Field	Name	n. patents	% patents
29	Other special machines	36,586	13.30%
1	Electrical machinery, apparatus, energy	28,388	10.32%
23	Chemical engineering	24,21	8.80%
25	Manufacture of electronic components and boards	23,59	8.57%
24	Handling	22,669	8.24%
35	Civil engineering	18,165	6.60%
20	Materials, metallurgy	17,978	6.53%
19	Basic materials chemistry	17,55	6.38%
28	Textile and paper machines	17,21	6.25%
32	Transport	17,126	6.22%

Table 7. Distribution of CE patents across IPC technological fields.

1.5.1.7 Main Actors

At the company level, Table 6 presents the top ten patent applicants in CE. The leader of the list is Procter & Gamble, known for its consumer goods, including household and personal care products, with 3,631 patents, accounting for 1.32% of the total. Samsung Electronics Co. Ltd., a leader in consumer electronics, follows with 3,506 patents (1.27%). Siemens AG, a multinational company focused on industrial automation, energy, healthcare and digital transformation, ranks third with 3,305 patents (1.20%), just ahead of Robert Bosch GmbH, which holds 3,200 patents (1.16%) and specializes in engineering and electronics. Novozymes A/S, a biotechnology company, follows closely with 3,151 patents (1.15%). Other notable contributors include Hewlett Packard Development Co. LP and Matsushita Electric Industrial Co. Ltd. The leading actors are especially focused on the 5R principles, as illustrated in Table A.12. Procter & Gamble's dominance is particularly evident in "Reduce" and "Refurbish", as their innovations aim to reduce resource consumption in consumer goods and enhance product longevity. Samsung Electronics and Siemens AG are pivotal in "Repair," leveraging advancements in electronic components and modular systems. Robert Bosch GmbH demonstrates strong engagement with "Recycle" through its contributions to material recovery technologies. Meanwhile, Novozymes A/S drives innovation in "Reuse," with biobased solutions enabling the reintegration of biological materials into production cycles. Looking at the leading actors by CE topic in Table 13, the data reveal a diverse range of company specializations across CE topics within the circular economy. In "Material

and process innovation”, Hewlett Packard Development Co. LP and LG Electronics prevails (0.67%), while in “Adaptive structures and materials”, Novozymes A/S stands out with 728 patents (0.948%). For “Imaging and Display Technologies”, Samsung Electronics Co. Ltd. excels with 510 patents (1.483%). “Adaptive Structures and Materials” is once again notably influenced by the activities of Hewlett Packard Development Co. LP, while in “Agriculture and Resource Optimization”, E.I. du Pont de Nemours & Co prevails among others.

	Name	n. patents	% patents
1	Procter & Gamble	3,631	1.32%
2	Samsung Electronics Co., Ltd.	3,506	1.27%
3	Siemens AG	3,305	1.20%
4	Robert Bosch GmbH	3,2	1.16%
5	Novozymes A/S	3,151	1.15%
6	Hewlett Packard Development Company, L.P.	2,723	0.99%
7	Matsushita Electric Industrial Co., Ltd.	2,644	0.96%
8	BASF SE	2,627	0.96%
9	E.I. du Pont de Nemours and Company & CO	2,488	0.90%
10	LG Electronics	2,481	0.90%

Table 8. Top applicants.

1.5.1.8 Appendix

Topic	Title	Description	n. patents	% patents
2	Adaptive Structures and Materials	This topic focuses on the design, manufacture, and application of collapsible, foldable, or layered structures integrated with advanced materials. These structures are developed using shaping, joining, and compounding processes, enabling flexible, multifunctional, and lightweight solutions.	63,242	22.99%
1	Material and Process Innovation	This topic focuses on innovative approaches to materials and processes, emphasizing the development of new technologies to improve functionality, sustainability, and efficiency across various sectors.	54,833	19.93%
3	Polymers, Composites, and Material Recycling	This topic focuses on advancements in polymer and composite materials, their synthesis, applications, and recycling processes, emphasizing sustainable material use and circular economy principles.	46,164	16.78%
4	Resource Recovery	This topic addresses processes and technologies for water purification, wastewater treatment, and the recovery of resources such as energy, nutrients, and biogas from organic and industrial waste streams.	23,419	8.51%

6	Imaging and Display Technologies	This topic explores innovations in imaging, display, and sensor technologies, with applications in electronics, visual systems, and devices for communication and interaction.	20,757	7.54%
5	Recycling Equipment and Waste Management	This topic addresses equipment and processes for waste sorting, recycling, and disposal, including pyrolysis, crushing, separation mechanisms, and machinery for handling plastics, metals, and other materials.	20,496	7.45%
9	Data Communication and Digital Systems	This topic encompasses the development and application of digital systems used for communication, data transmission, and secure transactions. It includes technologies like cloud computing, blockchain, cryptography, and telecommunications, with a focus on improving energy efficiency, reducing emissions, and optimizing resource use.	16,067	5.84%
8	Battery Technologies and Recycling	This topic covers advancements in batteries and energy storage, emphasizing recycling, electrochemical processes, and materials for efficient and sustainable energy systems.	13,204	4.80%
7	Resource and Material Efficiency	This topic emphasizes the efficient use of resources and materials across industries, focusing on reducing waste, optimizing supply chains, and enhancing resource recovery through advanced processes and technologies	11,663	4.24%

10	Agriculture and Resource Optimization	This topic focuses on sustainable agricultural practices, optimizing soil management, nutrient cycles, and resource use for efficient cultivation and farming systems.	5,168	1.87%
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Table A 1. Distribution of patents by 10 CE topics

Topic	Example a	Example b	Example c
Material and Process Innovation	The invention relates to an installation for purifying a fibrous suspension, having multiple hydrocyclones (1) arranged adjacent to one another in a row, which hydrocyclones each have at least one feed connection (2), one accepted stock connection (3) and one reject material connection (4), and having at least one supply collecting line (5) which is connected to multiple feed connections (2) and which serves for the feed of the fibrous suspension, and/or having at least one accepted stock collecting line (6) which is connected to multiple accepted stock connections (3) and which serves for the drainage of the accepted stock [...]. Devices and methods for cleaning an array	A recyclable, laminated polyolefin-based film structure comprises two or more film plies laminated to each other. Each of the laminated film plies comprises one or more polyolefin-based films. The film structure has an energy-cured coating layer disposed on the outermost outward facing surface of the film structure and a printed ink layer on an interior surface of one of the polyolefin-based polyolefin layers.	According to one embodiment, a method for generating a dynamic watering plan that reduces water consumption requirements for vegetation is disclosed. An example method includes estimating root depth of vegetation watered by a watering system; determining an allowed water depletion threshold of the vegetation based on the root depth; determining a training watering plan to increase the root depth of the vegetation over time based on the root depth and the allowed water depletion threshold; and transmitting the training watering plan to a flow controller for execution by the watering system.
Adaptive Structures and Materials	Devices and methods for cleaning an array of solar panels in side-by-side relation employ one or more elongated	A watchband, the watchband comprising: a substantially non-flexible main member (100A, 100B); a flexible	Collapsible reusable carrying cases are provided in sizes varying from small food containers to large

	flexible elements, preferably implemented as translucent strips (14a, 14b, 14c, 14d), anchored at their ends relative to the array of solar panels (12). Each strip spans two or more solar panels, and is wind-displaceable so as to contribute to cleaning of at least two of the solar panels (12).	auxiliary member (102) coupled to the substantially non-flexible main member (100A, 100B); and a tensioning member (104) coupled to the flexible auxiliary member (102). In use, the tensioner (104) is configured to maintain a selected degree of tension, and the flexible auxiliary member (102) is configured to be resilient.	push cart bins on casters. The cases are assembled or disassembled from a joined flat space-saving configuration to a functioning case and vice-versa. All parts that make up a carrying case do not separate from the carrying case and no parts can be removed. The cases are formed from rigid plastic panels, and are assembled or disassembled without tools. [...] The carrying cases are resistant to water, dirt, bacteria, molds, allergens, and inclement weather.
Polymers, Composites, and Material Recycling	Provided are a method and an apparatus for manufacturing a fiber-reinforced resin molding material by which, when the fiber-reinforced resin molding material is manufactured, separated fiber bundles can be supplied to a cutting machine in stable condition while avoiding the influence of meandering of the fiber bundles or slanting or meandering of filaments occurring in the fiber bundles. A method for manufacturing a sheet-shaped fiber-reinforced resin molding material in which spaces between filaments of cut-out fiber bundles (CF) are impregnated with resin includes [...].	A method of upcycling polymers to use-ful hydrocarbon materials. A catalyst with nanoparticles on a substrate selectively docks and cleaves longer hydro-carbon chains over shorter hydrocarbon chains. The nanoparticles exhibit an edge to facet ratio to provide for more interactions with the facets.	A resealable beverage can lid has a lid having a top side having a score line forming a panel, a first rivet formed in the lid and extending outwardly from the top side of the lid, a second rivet formed in the panel and extending outwardly from the top side of the lid, and a tab portion connected to the first rivet and the second rivet.
Resource Recovery	The disclosed technology includes blister package assemblies that include a reusable blister pouch. The blister package assembly can	Hydro excavation vacuum apparatus that process spoil material onboard the apparatus by separating water from the cut earthen material are disclosed. C)0 (N	A semiconductor apparatus may include a repair circuit configured to activate a redundant line of a cell array region by comparing repair

	have an enclosure housing having a first card and a second card. The second card can be opposed to a separably joinable to the first card. The blister package assembly can have a reusable blister pouch that can enclose an object and have a fastener that transition the reusable blister pouch between an open configuration and a closed configuration.		information and address information. The semiconductor apparatus may include a main decoder configured to perform a normal access to the cell array region by decoding the address information. The address information may include both column information and row information.
Waste Management and Recycling Equipment	A knife is provided that includes a replaceable blade element. The knife employs a blade carrier that is fixedly interconnected to or foldable with respect to a handle. The blade carrier selectively receives the replaceable blade element that is locked into the blade carrier by way of a hook and movable pin combination. The replaceable blade element is designed to be inserted within the blade carrier quickly, easily, and safely.	Systems and methods for detecting a waste receptacle, the system including a camera for capturing an image, a convolutional neural network, and processor. The convolutional neural network can be trained for identifying target waste receptacles. The processor can be mounted on the waste-collection vehicle and in communication with the camera and the convolutional neural network configured for using the convolutional neural network. The processor can be configured for using the convolutional neural network to generate an object candidate based on the image [...]	Systems and methods for classifying and sorting of plastic materials utilizing a vision system and one or more sensor systems, which may implement a machine learning system in order to identify or classify each of the materials, which may then be sorted into separate groups based on such an identification or classification.
Imaging and Display Technologies	A material sorting system sorts materials utilizing a vision system that implements a machine learning system in order to identify or classify each of the materials, which are then sorted into separate groups based on such an identification or classification. The material sorting system may include an x-ray fluorescence system to	A bifacial solar module with enhanced power output including first and second transparent support layers, a plurality of electrically interconnected bifacial solar cells arranged between the transparent support layers with gaps between one or more of the interconnected solar cells and edges of the first and second transparent	A device and/or apparatus that comprises a dynamic optical lens is provided. A first apparatus includes a first lens component having a first surface and a second surface. The first apparatus further includes a second lens component that comprises a flexible element. [...] The flexible element of the

	perform a classification of the materials in combination with the vision system, whereby the classification efforts of the vision system and x-ray fluorescence system are combined in order to classify and sort the materials.	support layers, the bi-facial solar cells having a first side directly exposed to solar radiation and a second side opposite the first. The bifacial solar module further includes one or more micro-structured reflective tapes positioned coincidentally with the gaps and attached to a surface of the second support layer such that light passing through the second support layer is reflected back into the second support layer at angles such that light reflecting from the tape is absorbed by either the first or second side of the bifacial solar cells.	second lens component is such that it conforms to the first surface of the first lens component when an amount of fluid between the first surface of the first lens component and the second lens component is sufficiently low. The flexible element of the second lens component is also such that it does not conform to the first surface of the first lens component when an amount of fluid between the first surface of the first lens component and the second lens component is sufficiently great.
Resource and Material Efficiency	The invention relates to the supplemental generation of energy from operation of a train, and specifically to the generation of energy in connection to the rotation of disc brake rotors in combination with generators. Rotation of the disc brake rotors creates rotational energy that is transmitted to the generators, which then transmits the energy to a series of batteries for storage. The batteries may be stored in the platform for the train and/or within the train car itself. Energy from the batteries may be utilized by removal of the batteries from the train or through a number of outlets, sockets or connectors associated with the train car or platform.	[Problem] To provide a building material having excellent durability. [Solution] A building material having a convex part formed on a surface thereof, the convex part having a first lateral surface part and a second lateral surface part corresponding to the first lateral surface part. The building material is made of a mixture containing a hydraulic material, an admixture, and a plant-based reinforcing material. The plant-based reinforcing material, at least in the convex part, is distributed in the mixture with the hydraulic material and the admixture attached thereto. The distribution of the plant-based reinforcing material in the first lateral surface part and the distribution of the plant-based reinforcing material in the second lateral	Described herein are compositions and methods for waste-to-energy ash in engineered aggregate in road construction.

		surface part are substantially the same. [...]	
Battery Technologies and Recycling	The invention relates to a system for wirelessly charging an electrically chargeable device, in particular a mobile inspection robot, in a potentially explosive environment. The invention also relates to a charging station for use in such a system according to the invention. The invention further relates to an electrically chargeable device, in particular an inspection robot, for use in such a system according to the invention. [...]	The present invention provides a secondary battery which comprises an electrode assembly and an outer package that houses the electrode assembly. With respect to this secondary battery, the outer package is provided with a metal plate that is bonded thereto with an insulating material being interposed therebetween; the outer package has an opening; and either the peripheral edge of the opening or the outer edge of the metal plate is bent so as to be away from the insulating material.	A process for removal of aluminium and iron in the recycling of rechargeable batteries comprising providing a leachate from black mass, adding phosphoric acid (H ₃ PO ₄) to said leachate and adjusting the pH to form iron phosphate (FePO ₄) and aluminium phosphate (AlPO ₄), precipitating and removing the formed FePO ₄ and AlPO ₄ , and forming a filtrate for further recovery of cathode metals, mainly NMC- metals and lithium.
Data Communication and Digital Systems	A computer-based system collects data associated with a user activity. The data is transmitted from an app running on a computing device with a user account authenticated by the computer-based system. A carbon footprint of the user activity is calculated based on the data associated with the user activity. The system calculates a proof of environmental impact in response to a function of the carbon footprint and a baseline value. An amount of cryptocurrency is generated based on the proof of environmental impact by writing a transaction for the amount of cryptocurrency to a blockchain in response to proof of environmental impact.	A method for providing economic information based on geographic parameters that includes providing a map for display on a device, receiving a user-defined area on the map, and providing data relating to the user-defined area. Obtaining the relevant information or data about a particular geographic region frequently involves consulting a plurality of sources. The current method is much more efficient and cost effective to retrieve from fewer sources and provide the information in a quick and easy to comprehend format.	A computer-implemented system and method for inferring operational specifications of a photovoltaic power generation system using net load is provided. Photovoltaic plant configuration specifications can be accurately inferred with net load data and measured solar resource data. A time series of net load data is evaluated to identify, if possible, a time period with preferably minimum and consistent power consumption. Power generation data is simulated for a range of hypothetical photovoltaic system configurations based on a normalized solar power simulation model. Net load data is estimated based on a base load and, if

	The amount of cryptocurrency is assigned to the user account authenticated with the computer-based system.		applicable, any binary loads and any variable loads.
Agriculture and Resource Optimization	Techniques for providing improvements in agricultural science by optimizing irrigation treatment placements for testing are provided, including analyzing a plurality of digital images of a field to determine vegetation density changes in a sector of the field. The techniques proceed by comparing a distribution of pixel characteristics in the digital images for each field sector to determine sectors in which minimal density deviations are present. Instructions for irrigation placements and testing may be displayed or modified based on the results of the sector determinations.	Implementations are described herein for edge-based real time crop yield pre- dictions made using sampled subsets of robotically-acquired vision data. In various implementations, one or more robots may be deployed amongst a plu- rality of plants in an area such as a field. [...] A subset of multiple high resolu- tion images may then be sampled from the superset of high resolution images. Data indicative of the subset of high resolution images may be applied as in- put across a machine learning model, with or without additional data, to generate output indicative of a real time crop yield prediction.	System and method for treating harvested plant material, such as cannabis, with ozone. Embodiments include tum- bling the plant material in a rotating vessel, such as a drum, while exposing the plant material to ozone.

Table A 2. Examples CE topics.

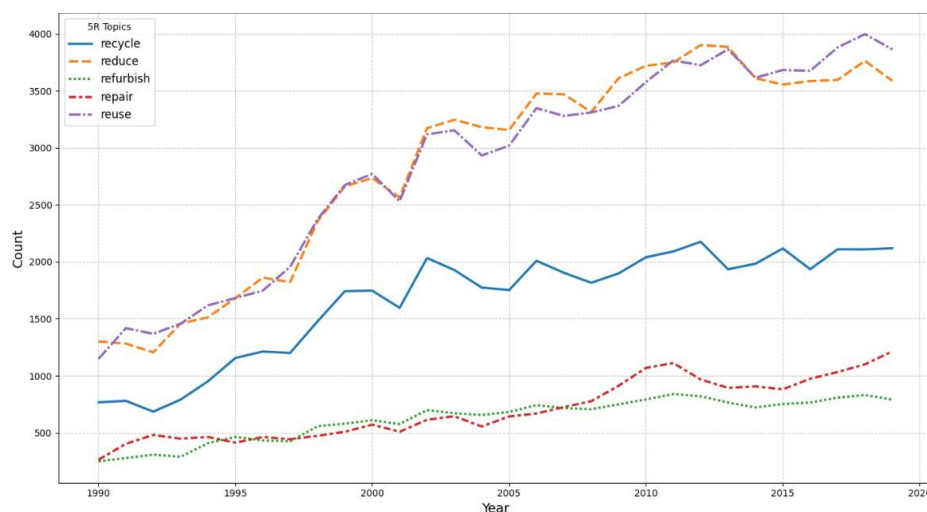


Figura A 1. Annual trend by 5R topics.

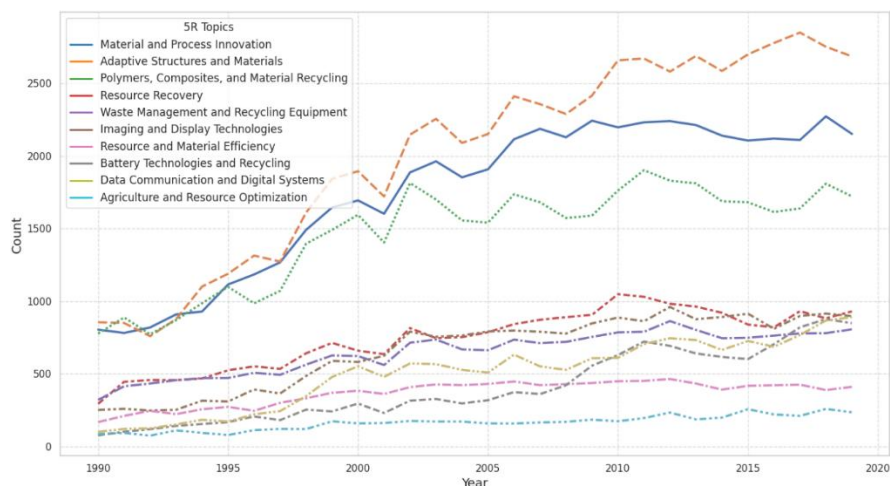


Figura A 2. Annual trend by CE topics.

	NUTS Code	Region Name	n. patents	% patents
1	DE212	Main-Kinzig-Kreis, Germany	5,382	2.08%
2	FR101	Paris, France	4,06	1.57%
3	FI1B1	Helsinki-Uusimaa, Finland	3,179	1.23%
4	FR105	Hauts-de-Seine, France	3,101	1.20%
5	CH040	Zurich, Switzerland	2,817	1.09%
6	NL414	Flevoland, Netherlands	2,595	1.00%
7	ITC4C	Milan, Italy	2,542	0.98%
8	DK012	Copenhagen City, Denmark	2,359	0.91%
9	DE111	Region Hannover, Germany	2,257	0.87%
10	SE224	Västra Götaland, Sweden	2,191	0.84%

Table A 3. Distribution of CE patents at Nuts3 level.

Topic	NUTS3 Code	Region Name	n. patents	% patents
Reduce	DE212	Main-Kinzig-Kreis, Germany	1,446	1.90%
	FR101	Paris, France	1,23	1.62%
	NL414	Flevoland, Netherlands	1,114	1.47%

	FIIB1	Helsinki-Uusimaa, Finland	1,02	1.34%
	FR105	Hauts-de-Seine, France	908	1.20%
	ITC4C	Milan, Italy	847	1.12%
	CH040	Zurich, Switzerland	816	1.07%
	CH011	Lausanne, Switzerland	739	0.97%
	DK012	Copenhagen City, Denmark	722	0.95%
	SE110	Stockholm, Sweden	708	0.93%
Reuse	DE212	Main-Kinzig-Kreis, Germany	1,638	1.85%
	FR101	Paris, France	1,476	1.67%
	DK012	Copenhagen City, Denmark	1,263	1.43%
	FIIB1	Helsinki-Uusimaa, Finland	1,221	1.38%
	DEA11	Düsseldorf, Germany	1,099	1.24%
	FR105	Hauts-de-Seine, France	1,014	1.14%
	CH040	Zurich, Switzerland	915	1.03%
	NL414	Flevoland, Netherlands	901	1.02%
	ITC4C	Milan, Italy	851	0.96%
	DEB34	Region Hannover, Germany	782	0.88%
Recycle	DE212	Main-Kinzig-Kreis, Germany	1,643	2.88%
	FR101	Paris, France	783	1.37%
	DE111	Region Hannover, Germany	686	1.20%
	FR105	Hauts-de-Seine, France	675	1.18%
	CH040	Zurich, Switzerland	668	1.17%
	FIIB1	Helsinki-Uusimaa, Finland	531	0.93%
	DE115	Karlsruhe, Germany	519	0.91%
	DE929	Gießen, Germany	506	0.89%
	ITC4C	Milan, Italy	497	0.87%
	DE600	Hamburg, Germany	453	0.79%
Repair	DE212	Main-Kinzig-Kreis, Germany	279	1.61%
	FR101	Paris, France	262	1.51%
	FIIB1	Helsinki-Uusimaa, Finland	231	1.33%

	DE111	Region Hannover, Germany	207	1.19%
	FR105	Hauts-de-Seine, France	206	1.19%
	CH040	Zurich, Switzerland	199	1.14%
	DE300	Berlin, Germany	193	1.11%
	SE110	Stockholm, Sweden	184	1.06%
	ITC4C	Milan, Italy	176	1.01%
	DE600	Hamburg, Germany	152	0.87%
	Refurbish			
	DE212	Main-Kinzig-Kreis, Germany	376	1.86%
	SE224	Västra Götaland, Sweden	324	1.60%
	FR101	Paris, France	309	1.53%
	FR105	Hauts-de-Seine, France	298	1.47%
	CH040	Zurich, Switzerland	212	1.05%
	DE600	Hamburg, Germany	203	1.00%
	FI1B1	Helsinki-Uusimaa, Finland	176	0.87%
	FR714	Haute-Garonne, France	173	0.86%
	ITC4C	Milan, Italy	171	0.85%
	DE111	Region Hannover, Germany	139	0.69%

Table A 4. Distribution of patents per 5R topics across at Nuts3 level.

Topic	NUTS Code	Region Name	n. patents	% patents
Material and Process Innovation	DE212	Main-Kinzig-Kreis, Germany	1,048	2.11%
	FR101	Paris, France	802	1.62%
	CH040	Zurich, Switzerland	566	1.14%
	FR105	Hauts-de-Seine, France	566	1.14%
	DE11C	Düsseldorf, Germany	495	1.00%
	ITC4C	Lombardy, Italy	477	0.96%
	DE111	Stuttgart, Germany	452	0.91%
	FI1B1	Uusimaa, Finland	431	0.87%

Polymers, Composites, and Material Recycling	CH011	Lausanne, Switzerland	429	0.87%
	ITH55	Tuscany, Italy	417	0.84%
	DK012	Copenhagen, Denmark	1,443	2.55%
	DE212	Main-Kinzig- Kreis, Germany	952	1.68%
	FI1B1	Uusimaa, Finland	945	1.67%
	FR101	Paris, France	863	1.53%
	DEA11	Düsseldorf, Germany	821	1.45%
	DEB34	Karlsruhe, Germany	751	1.33%
	DK013	Zealand, Denmark	688	1.22%
	CH011	Lausanne, Switzerland	659	1.17%
	FR105	Hauts-de-Seine, France	563	0.99%
	CH040	Zurich, Switzerland	541	0.96%
Imaging and Display Technologies	NL414	North Brabant, Netherlands	426	2.71%
	DE212	Main-Kinzig- Kreis, Germany	417	2.66%
	FR101	Paris, France	361	2.30%
	FR105	Hauts-de-Seine, France	246	1.57%
	DE11D	Upper Bavaria, Germany	222	1.41%
	ITC4C	Lombardy, Italy	219	1.39%
	FR107	Rhône, France	200	1.27%
	FR714	Provence-Alpes- Côte d'Azur, France	193	1.23%
	SE110	Stockholm, Sweden	185	1.18%
	CH040	Zurich, Switzerland	177	1.13%
Adaptive Structures and Materials	DE212	Main-Kinzig- Kreis, Germany	1,402	2.32%
	FI1B1	Uusimaa, Finland	741	1.23%

	NL414	North Brabant, Netherlands	717	1.19%
	SE224	Västra Götaland, Sweden	681	1.13%
	FR101	Paris, France	675	1.12%
	ITH34	Emilia-Romagna, Italy	662	1.10%
	ITC4C	Lombardy, Italy	646	1.07%
	DE929	Bavaria, Germany	601	0.99%
	FR105	Hauts-de-Seine, France	596	0.99%
	DE111	Stuttgart, Germany	588	0.97%
Agriculture and Resource Optimization	DK012	Copenhagen, Denmark	114	2.21%
	DE300	Berlin, Germany	94	1.82%
	FR101	Paris, France	84	1.63%
	ITC4C	Lombardy, Italy	72	1.39%
	NL221	Groningen, Netherlands	71	1.37%
	FI1B1	Uusimaa, Finland	61	1.18%
	DEB3I	Freiburg, Germany	59	1.14%
	DEA1C	Lower Saxony, Germany	59	1.14%
	DK013	Zealand, Denmark	59	1.14%
	DEA1I	Düsseldorf, Germany	59	1.14%
Data Communication and Digital Systems	DE212	Main-Kinzig-Kreis, Germany	408	4.31%
	SE110	Stockholm, Sweden	225	2.38%
	FR105	Hauts-de-Seine, France	208	2.20%
	FR101	Paris, France	208	2.20%
	SE224	Västra Götaland, Sweden	167	1.77%
	FI1B1	Uusimaa, Finland	165	1.74%
	NL414	North Brabant, Netherlands	154	1.63%

	CH040	Zurich, Switzerland	147	1.55%
	DE111	Stuttgart, Germany	130	1.37%
	UKH12	East of England, UK	94	0.99%
Resource and Material Efficiency	FR101	Paris, France	234	1.92%
	CH040	Zurich, Switzerland	230	1.89%
	FR105	Hauts-de-Seine, France	222	1.82%
	DE212	Main-Kinzig- Kreis, Germany	169	1.39%
	DE128	Bremen, Germany	140	1.15%
	CH033	Espace Mittelland, Switzerland	139	1.14%
	DEA11	Düsseldorf, Germany	136	1.12%
	FR714	Provence-Alpes- Côte d'Azur, France	131	1.07%
	DE125	Baden- Württemberg, Germany	119	0.98%
	DK013	Zealand, Denmark	119	0.98%
Resource Recovery	FR101	Paris, France	369	1.86%
	FR105	Hauts-de-Seine, France	355	1.79%
	DE212	Main-Kinzig- Kreis, Germany	345	1.74%
	FR103	Île-de-France, France	253	1.28%
	FI1B1	Uusimaa, Finland	233	1.17%
	SE224	Västra Götaland, Sweden	215	1.08%
	CH040	Zurich, Switzerland	211	1.06%
	DE111	Stuttgart, Germany	209	1.05%
	ITC4C	Lombardy, Italy	205	1.03%

	SE110	Stockholm, Sweden	175	0.88%
Battery Technologies and Recycling	FR101	Paris, France	247	3.03%
	DE212	Main-Kinzig- Kreis, Germany	236	2.90%
	DE111	Stuttgart, Germany	235	2.88%
	FR714	Provence-Alpes- Côte d'Azur, France	181	2.22%
	CH011	Lausanne, Switzerland	136	1.67%
	NL414	North Brabant, Netherlands	128	1.57%
	FR105	Hauts-de-Seine, France	123	1.51%
	DEB34	Karlsruhe, Germany	117	1.44%
	CH040	Zurich, Switzerland	116	1.42%
	DE300	Berlin, Germany	102	1.25%
Recycling Equipment and Waste Management	DE115	Freiburg, Germany	461	2.08%
	DE212	Main-Kinzig- Kreis, Germany	358	1.61%
	FI1B1	Uusimaa, Finland	279	1.26%
	BE251	Flanders, Belgium	269	1.21%
	AT312	Upper Austria, Austria	254	1.15%
	CH040	Zurich, Switzerland	235	1.06%
	DE111	Stuttgart, Germany	224	1.01%
	FR101	Paris, France	217	0.98%
	DEA11	Düsseldorf, Germany	211	0.95%
	NL414	North Brabant, Netherlands	196	0.88%

Table A 5. Distribution of patents by CE topics across at Nuts3 level.

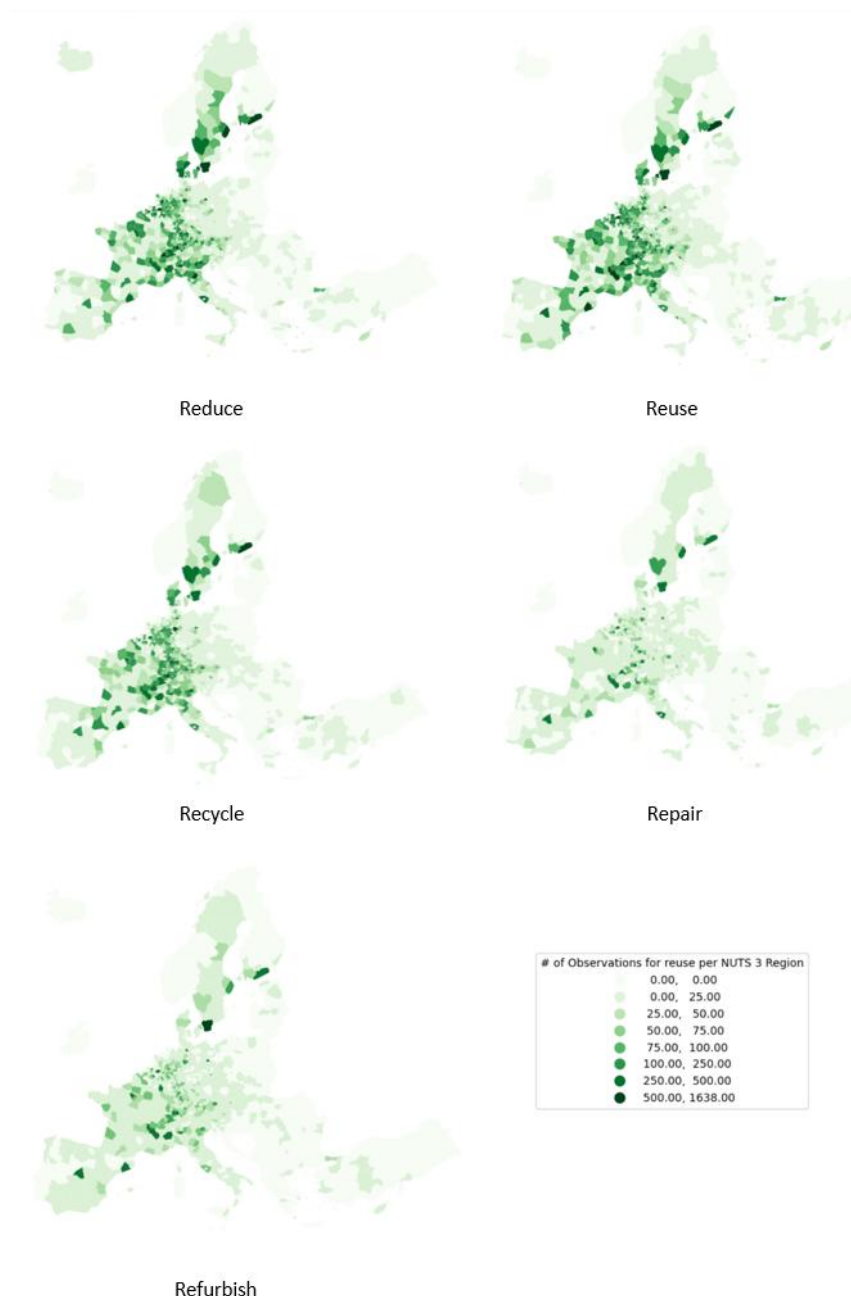


Figura A 3. Distribution of CE patents by 5R topics at Nuts3 level.

Topic	CPC Code	CPC Title	n. patents	% patents
Reduce	H01M	Processes or means, e.g., batteries	40,806	5.80 %
	B01D	Separation	30,033	4.27%
	C02F	Treatment of water, waste water, sewage, or sludge	29,145	4.14%

	H01L	Semiconductor devices not covered by class H10	19,264	2.74%
	B29C	Shaping or joining of plastics	18,8	2.67%
	B32B	Layered products, i.e., products built-up of strata of flat or non-flat	16,934	2.41%
	B65D	Containers for storage or transport of articles or materials	16,343	2.32%
	Y10T	Technical subjects covered by former US classification	15,359	2.18%
	Y02E	Reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution	13,918	1.98%
	G06F	Electric digital data processing	13,633	1.94%
Recycle	B29C	Shaping or joining of plastics	28,654	7.37%
	B32B	Layered products, i.e., products built-up of strata of flat or non-flat	18,9	4.86%
	Y10T	Technical subjects covered by former US classification	13,954	3.59%
	B65D	Containers for storage or transport of articles or materials	10,498	2.70%
	H01L	Semiconductor devices not covered by class H10	9,703	2.50%
	C02F	Treatment of water, waste water, sewage, or sludge	8,617	2.22%
	H01M	Processes or means, e.g., batteries, for the direct conversion of chemical energy into electrical energy	6,511	1.68%
	G06F	Electric digital data processing	6,34	1.63%
	F16C	Shafts; flexible shafts; elements or crankshaft mechanisms; rotary bodies other than gearing elements	5,883	1.51%
	C04B	Lime, magnesia; slag; cements; compositions thereof	5,486	1.41%
Repair	H01M	Processes or means, e.g., batteries	23,494	11.90%
	C02F	Treatment of water, waste water, sewage, or sludge	21,302	10.79%
	Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	9,677	4.90%
	B01D	Separation	9,202	4.66%

	Y02E	Reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution	7,326	3.71%
	H01L	Semiconductor devices not covered by class H10	5,48	2.78%
	A47L	Domestic washing or cleaning	5,003	2.53%
	B65D	Containers for storage or transport of articles or materials	4,355	2.21%
	B32B	Layered products, i.e., products built-up of strata of flat or non-flat, e.g., cellular or honeycomb, form	4,352	2.20%
	Y02P	Climate change mitigation technologies in the production or processing of goods	3,941	2.00 %
Refurbish	B32B	Layered products, i.e., products built-up of strata of flat or non-flat	23,874	14.27 %
	B29C	Shaping or joining of plastics	9,225	5.51%
	Y10T	Technical subjects covered by former US classification	6,927	4.14%
	H01L	Semiconductor devices not covered by class H10	6,785	4.05 %
	C04B	Lime, magnesia; slag; cements; compositions thereof; artificial stone; ceramics; refractories; treatment of natural stone	5,673	3.38%
	B65D	Containers for storage or transport of articles or materials	3,596	2.14%
	C02F	Treatment of water, waste water, sewage, or sludge	3,481	2.08 %
	E04F	Finishing work on buildings	3,203	1.91%
	B01D	Separation	2,807	1.67%
	E04B	General building constructions	2,767	1.65%

Table A 6. Distribution of patents per 5R topic across CPC codes.

Topic	CPC Code	CPC Title	n. patents	% patents
Material and Process Innovation	B65D	Containers for storage or transport of articles or materials	23,69	5.66%
	H01L	Semiconductor devices not covered by class H10	21,797	5.21%
	B29C	Shaping or joining of plastics	21,1	5.04%

	B32B	Layered products	14,689	3.51%
	H01M	Processes or means, e.g., batteries, for the direct conversion of chemical energy into electrical energy	14,01	3.35%
	B01D	Separation	12,55	3.00%
	Y10T	Technical subjects covered by former US classification	11,098	2.65%
	C02F	Treatment of water, waste water, sewage, or sludge	9,953	2.38%
	B01L	Chemical or physical laboratory apparatus for general use	9,156	2.19%
	B41J	Typewriters; selective printing mechanisms	8,261	1.97%
Polymers, Composites, and Material Recycling	B32B	Layered products	40,999	10.29%
	B29C	Shaping or joining of plastics	29,022	7.29%
	C12N	Microorganisms or enzymes; compositions thereof; genetic engineering	16,034	4.03%
	Y10T	Technical subjects covered by former US classification	15,657	3.93%
	C08J	Working-up; general processes of compounding	13,199	3.31%
	C08L	Compositions of macromolecular compounds	10	2.51%
	B29K	Indexing scheme associated with moulding materials or materials for moulds	9,764	2.45%
	B65D	Containers for storage or transport of articles or materials	9,102	2.28%
	B01J	Chemical or physical processes, e.g., catalysis	9,062	2.27%
	C04B	Lime, magnesia; slag; cements	8,18	2.05%
Imaging and Display Technologies	G02B	Optical elements, systems or apparatus	15,572	9.30%
	H01L	Semiconductor devices not covered by class H10	14,455	8.63%
	B32B	Layered products	8,362	5.00%
	H04N	Pictorial communication, e.g., television	7,31	4.36%

	G06F	Electric digital data processing	5,223	3.12%
	G02F	Optical devices or arrangements for the control of light	4,39	2.62%
	Y10T	Technical subjects covered by former US classification	3,877	2.31%
	C08L	Compositions of macromolecular compounds	3,837	2.29%
	G06T	Image data processing or generation	3,779	2.26%
	B29C	Shaping or joining of plastics	3,598	2.15%
Adaptive Structures and Materials	B29C	Shaping or joining of plastics; shaping of materials or articles made of plastics	29,572	6.29%
	B32B	Layered products, i.e., products built-up of strata of flat or non-flat materials	26,361	5.61%
	Y10T	Technical subjects covered by former US classification	17,634	3.75%
	A43B	Characteristic features of footwear	16,088	3.42%
	B65D	Containers for storage or transport of articles or materials	12,836	2.73%
	H01L	Semiconductor devices not covered by class H10	12,52	2.66%
	H01M	Processes or means, e.g., batteries, for the direct conversion of chemical energy into electrical energy	9,324	1.98%
	B33Y	Additive manufacturing, e.g., 3D printing	8,218	1.75%
	B22F	Working metallic powder; manufacture of articles from metallic powder	8,113	1.73%
	G06F	Electric digital data processing	6,665	1.42%
Agriculture and Resource Optimization	C12N	Microorganisms or enzymes; compositions thereof; genetic engineering; culture media	2,613	7.41%
	C02F	Treatment of water, waste water, sewage, or sludge	1,906	5.40%

	C05F	Organic fertilisers not covered by subclasses C05B, C05C, e.g. fertilisers from waste or refuse	1,469	4.16%
	C12P	Fermentation or enzyme-using processes to synthesise a desired chemical compound or composition	1,249	3.54%
	A23L	Foods, foodstuffs, or non-alcoholic beverages	1,242	3.52%
	H01M	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	1,178	3.34%
	Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	1,142	3.24%
	A01N	Preservation of bodies of humans or animals or plants or parts thereof	1,085	3.07%
	A01G	Horticulture; cultivation of vegetables	968	2.74%
	Y02P	Climate change mitigation technologies in the production or processing of goods	852	2.41%
Data Communication and Digital Systems	G06F	Electric digital data processing	12,096	9.02%
	H04L	Transmission of digital information	9,076	6.77%
	G06Q	Information and communication technology	8,709	6.50%
	H04N	Pictorial communication	6,817	5.08%
	H02J	Circuit arrangements or systems for supplying or distributing electric power	5,501	4.10%
	H01M	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	5,397	4.02%
	B60L	Propulsion of electrically-propelled vehicles	4,239	3.16%
	H04M	Telephonic communication	3,597	2.68%

Resource and Material Efficiency	H04W	Wireless communication networks	2,861	2.13%
	B29C	Shaping or joining of plastics	2,601	1.94%
	C04B	Lime, magnesia; slag; cements; compositions thereof	22,239	11.19%
	B32B	Layered products	4,92	5.11%
	Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	4,504	4.68%
	H01M	Processes or means	3,941	4.10%
	B01J	Chemical or physical processes, e.g. catalysis or colloid chemistry	2,17	2.25%
	Y10T	Technical subjects covered by former US classification	2,147	2.23%
	G11B	Information storage based on relative movement between record carrier and transducer	2,138	2.22%
	C02F	Treatment of water, waste water, sewage, or sludge	1,663	1.73%
	H04R	Loudspeakers, microphones, gramophone pick-ups or like acoustic electromechanical transducers	1,626	1.69%
	B29C	Shaping or joining of plastics	1,616	1.68%
Resource Recovery	C02F	Treatment of water, waste water, sewage, or sludge	46,014	10.32%
	B01D	Separation	18,782	9.46%
	Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	8,714	4.38%
	H01M	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	6,061	3.05%
	Y02E	Reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution	4,841	2.43%

	B01J	Chemical or physical processes, e.g. catalysis or colloid chemistry	4,616	2.32%
	C12M	Apparatus for enzymology or microbiology; bioreactors or fermenters	3,585	1.80%
	B32B	Layered products	3,543	1.78%
	H01L	Semiconductor devices not covered by class H10	3,236	1.63%
	F24S	Solar heat collectors; solar heat systems	3,062	1.54%
Battery Technologies and Recycling	H01M	Processes or means, e.g. batteries	57,519	7.84%
	Y02E	Reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution	8,719	6.29%
	H02J	Circuit arrangements or systems for supplying or distributing electric power	5,388	3.88%
	B60L	Propulsion of electrically-propelled vehicles	4,643	3.34%
	C01P	Indexing scheme relating to structural and physical aspects of solid inorganic compounds	3,184	2.29%
	Y02T	Climate change mitigation technologies related to transportation	3,159	2.27%
	Y02P	Climate change mitigation technologies in the production or processing of goods	2,805	2.02%
	H01L	Semiconductor devices not covered by class H10	2,706	1.95%
	H01G	Capacitors	2,001	1.44%
	B65D	Containers for storage or transport of articles or materials	1,978	1.42%
Recycling Equipment and Waste Management	B65D	Containers for storage or transport of articles or materials	1,978	5.01%
	B01D	Separation	13,002	4.95%
	B29C	Shaping or joining of plastics	6,128	3.90%

	Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	5,38	3.42%
	B29B	Preparation or pretreatment of the material to be shaped	4,498	2.86%
	B32B	Layered products, i.e. products built-up of strata of flat or non-flat form	4,346	2.76%
	H01M	Processes or means	4,173	2.65%
	F16C	Shafts; flexible shafts; elements or crankshaft mechanisms	4,046	2.57%
	B65D	Containers for storage or transport of articles or materials	3,915	2.49%
	C02F	Treatment of water, waste water, sewage, or sludge	3,701	2.35%
	Y10T	Technical subjects covered by former US classification	3,583	2.28%

Table A 7. Distribution of patents per CE topics across CPC codes.

Topic	NACE Code	NACE Title	n. patents	% patents
Reduce	20.10	Manufacture of basic chemicals	14,197	10.13%
	28.90	Manufacture of other special-purpose machinery	9,082	6.48%
	28.29	Manufacture of other general-purpose machinery	7,29	5.20%
	26.30	Manufacture of communication equipment	6,061	4.32%
	26.10	Manufacture of electronic components and boards	5,641	4.02%
	21.00	Manufacture of basic pharmaceutical products and preparations	5,501	3.92%
	26.20	Manufacture of computers and peripheral equipment	5,437	3.88%
	27.20	Manufacture of batteries and accumulators	5,191	3.70%
	29.10	Manufacture of motor vehicles	4,177	2.98%
	28.10	Manufacture of general-purpose machinery	4,172	2.98%

Reuse	20.10	Manufacture of basic chemicals	16,522	11.38%
	28.90	Manufacture of other special-purpose machinery	9,684	6.67%
	21.00	Manufacture of basic pharmaceutical products and preparations	7,782	5.36%
	22.00	Manufacture of rubber and plastic products	7,58	5.22%
	26.10	Manufacture of electronic components and boards	5,601	3.86%
	26.20	Manufacture of computers and peripheral equipment	4,333	2.99%
	32.90	Manufacturing	4,197	2.89%
	28.23	Manufacture of office machinery and equipment	4,161	2.87%
	26.30	Manufacture of communication equipment	4,047	2.79%
	23.50	Manufacture of cement, lime and plaster	3,999	2.76%
Recycle	28.10	Manufacture of general-purpose machinery	5,499	6.91%
	22.00	Manufacture of rubber and plastic products	5,07	6.37%
	20.10	Manufacture of chemicals and chemical products	5,023	6.31%
	29.10	Manufacture of motor vehicles	4,586	5.76%
	28.90	Manufacture of other special-purpose machinery	4,488	5.64%
	26.30	Manufacture of communication equipment	3,078	3.87%
	28.40	Manufacture of metal forming machinery and machine tools	3,06	3.85%
	26.10	Manufacture of electronic components and boards	2,725	3.43%
	26.50	Manufacture of instruments for measuring, testing and navigation	2,404	3.02%
	26.20	Manufacture of computers and peripheral equipment	2,246	2.82%
Repair	20.10	Manufacture of basic chemicals	7,726	21.56%
	28.90	Manufacture of other special-purpose machinery	3,006	8.39%
	27.20	Manufacture of batteries and accumulators	2,916	8.14%
	28.29	Manufacture of other general-purpose machinery	2,198	6.13%

	26.10	Manufacture of electronic components and boards	1,827	5.10%
	27.50	Manufacture of electric lighting equipment	1,195	3.33%
	28.99	Manufacture of other special-purpose machinery	1,078	3.01%
	22.20	Manufacture of plastics products	1,059	2.95%
	24.00	Manufacture of basic metals	728	2.03%
	29.10	Manufacture of motor vehicles	698	1.95%
Refurbish	20.10	Manufacture of basic chemicals	2,717	8.59%
	43.00	Specialised construction activities	2,429	7.68%
	28.90	Manufacture of other special-purpose machinery	2,036	6.44%
	22.00	Manufacture of rubber and plastic products	1,896	6.00%
	23.00	Manufacture of other non-metallic mineral products	1,841	5.82%
	26.10	Manufacture of electronic components and boards	1,695	5.36%
	29.10	Manufacture of motor vehicles	1,467	4.64%
	23.50	Manufacture of cement, lime and plaster	979	3.10%
	31.00	Manufacture of furniture	873	2.76%
	28.29	Manufacture of other general-purpose machinery	838	2.65%

Table A 8. Distribution of patents per 5R topics across NACE codes

Topic	NACE Code	NACE Title	n. patents	% patents
Material and Process Innovation	28.90	Manufacture of other special-purpose machinery	7,322	8.78%
	20.10	Manufacture of basic chemicals	6,525	7.83%
	26.10	Manufacture of electronic components and boards	4,807	5.77%
	32.90	Manufacturing	4,205	5.04%
	28.29	Manufacture of other general-purpose machinery	3,967	4.76%
	22.00	Manufacture of rubber and plastic products	3,53	4.23%
	27.50	Manufacture of domestic appliances & general-purpose machinery	3,316	3.98%

	28.10	Manufacture of general-purpose machinery	3,114	3.73%
	28.23	Manufacture of office machinery and equipment	3,023	3.63%
	26.50	Manufacture of instruments and appliances for measuring, testing, and navigation	2,564	3.08%
Polymers, Composites, and Material Recycling	20.10	Manufacture of basic chemicals	12,601	16.41%
	21.00	Manufacture of basic pharmaceutical products and preparations	8,75	11.39%
	22.00	Manufacture of rubber and plastic products	5,277	6.87%
	28.90	Manufacture of other special-purpose machinery	4,062	5.29%
	10.00	Manufacture of food products	3,844	5.01%
	23.00	Manufacture of other non-metallic mineral products	3,66	4.77%
	22.20	Manufacture of plastics products	1,715	2.23%
	26.50	Manufacture of instruments and appliances for measuring, testing, and navigation	1,652	2.15%
	28.29	Manufacture of other general-purpose machinery	1,637	2.13%
	13.00	Manufacture of textiles	1,626	2.12%
Imaging and Display Technologies	26.70	Manufacture of other electrical equipment	4,699	13.67%
	26.10	Manufacture of electronic components and boards	3,501	10.18%
	26.20	Manufacture of computers and peripheral equipment	2,879	8.37%
	26.30	Manufacture of communication equipment	2,742	7.98%
	20.10	Manufacture of basic chemicals	2,357	6.86%
	28.23	Manufacture of office machinery and equipment	1,857	5.40%
	26.50	Manufacture of instruments and appliances for	1,506	4.38%

		measuring, testing, and navigation		
	28.90	Manufacture of other special-purpose machinery	1,09	3.17%
	32.90	Manufacturing	1,036	3.01%
	27.40	Manufacture of electric lighting equipment	902	2.62%
Adaptive Structures and Materials	28.90	Manufacture of other special-purpose machinery	7,548	7.91%
	22.00	Manufacture of rubber and plastic products	6,734	7.05%
	28.10	Manufacture of general-purpose machinery	5,381	5.64%
	29.10	Manufacture of motor vehicles	4,911	5.14%
	43.00	Specialised construction activities	4,569	4.79%
	20.10	Manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	3,97	4.16%
	28.40	Manufacture of metal forming machinery and machine tools	3,904	4.09%
	26.10	Manufacture of electronic components and boards	3,555	3.72%
	32.00	Other manufacturing	3,51	3.68%
	15.00	Manufacture of leather and related products	3,302	3.46%
Agriculture and Resource Optimization	20.10	Manufacture of basic chemicals	1,666	20.90%
	21.00	Manufacture of basic pharmaceutical products and preparations	1,319	16.54%
	10.00	Manufacture of food products	753	9.44%
	28.30	Manufacture of other machinery	656	8.23%
	20.20	Manufacture of pesticides	441	5.53%
	20.20	Manufacture of pesticides and other agrochemical products	441	5.53%
	28.90	Manufacture of other special-purpose machinery	270	3.39%

	26.50	Manufacture of instruments and appliances for measuring, testing, and navigation	192	2.41%
	28.29	Manufacture of other general-purpose machinery	165	2.07%
	32.90	Manufacturing	165	2.07%
	22.00	Manufacture of rubber and plastic products	162	2.03%
Data Communication and Digital Systems	26.20	Manufacture of computers and peripheral equipment	3,958	15.54%
	26.30	Manufacture of communication equipment	3,896	15.29%
	62.00	Computer programming	2,089	8.20%
	28.23	Manufacture of office machinery	2,062	8.09%
	26.50	Manufacture of measuring instruments	1,345	5.28%
	26.50	Manufacture of instruments and appliances for measuring, testing, and navigation	1,345	5.28%
	27.12	Manufacture of electricity distribution and control apparatus	1,188	4.66%
	29.10	Manufacture of motor vehicles	1,086	4.26%
	27.20	Manufacture of batteries and accumulators	754	2.96%
	28.90	Manufacture of other special-purpose machinery	601	2.36%
	26.10	Manufacture of electronic components and boards	590	2.32%
Resource and Material Efficiency	23.50	Manufacture of cement, lime and plaster	4,129	21.95%
	20.10	Manufacture of basic chemicals	2,642	14.04%
	28.90	Manufacture of other special-purpose machinery	1,211	6.44%
	43.00	Specialised construction activities	1,106	5.88%
	24.00	Manufacture of basic metals	570	3.03%
	24.00	Manufacture of basic metals	570	3.03%
	23.30	Manufacture of clay building materials	564	2.99%

	27.20	Manufacture of batteries and accumulators	542	2.88%
	26.30	Manufacture of communication equipment	529	2.81%
	23.00	Manufacture of other non-metallic mineral products	461	2.45%
	22.00	Manufacture of rubber and plastic products	393	2.09%
Resource Recovery	20.10	Manufacture of basic chemicals	10,361	28.04%
	28.29	Manufacture of other general-purpose machinery	4,083	11.05%
	28.90	Manufacture of other special-purpose machinery	1,486	4.02%
	21.00	Manufacture of basic pharmaceutical products and preparations	1,263	3.42%
	32.50	Manufacture of electronic equipment	1,146	3.10%
	28.30	Manufacture of agricultural and forestry machinery	1,048	2.84%
	27.50	Manufacture of domestic appliances	977	2.64%
	26.10	Manufacture of electronic components and boards	946	2.56%
	28.99	Manufacture of other special-purpose machinery	939	2.54%
	27.20	Manufacture of batteries and accumulators	902	2.44%
Battery Technologies and Recycling	27.20	Manufacture of batteries and accumulators	6,816	33.80%
	20.10	Manufacture of basic chemicals	2,109	10.46%
	26.10	Manufacture of electronic components and boards	1,423	7.06%
	27.12	Manufacture of electric batteries	1,251	6.20%
	29.10	Manufacture of motor vehicles	838	4.16%
	28.90	Manufacture of other special-purpose machinery	571	2.83%
	27.90	Manufacture of other electrical equipment	496	2.46%
	24.00	Manufacture of basic metals	495	2.45%

	30.00	Manufacture of other transport equipment	382	1.89%
	28.23	Manufacture of office machinery and equipment	365	1.81%
Recycling Equipment and Waste Management	28.90	Manufacture of other special-purpose machinery	4,135	12.56%
	20.10	Manufacture of basic chemicals, fertilisers, nitrogen compounds, plastics, and synthetic rubber in primary forms	3,411	10.36%
	28.29	Manufacture of other general-purpose machinery	2,622	7.97%
	28.40	Manufacture of metal forming machinery and machine tools	1,883	5.72%
	22.20	Manufacture of rubber and plastic products	1,284	3.90%
	28.10	Manufacture of general-purpose machinery	1,225	3.72%
	28.99	Manufacture of other special-purpose machinery	1,133	3.44%
	22.00	Manufacture of rubber and plastic products	1,112	3.38%
	28.30	Manufacture of agricultural and forestry machinery	1,065	3.24%
	27.50	Manufacture of domestic appliances	1,012	3.07%

Table A 9. Distribution of patents per CE topics across NACE codes.

Topic	Tech. Field	Name	n. patents	% patents
Reduce	1	Electrical machinery, apparatus, energy	11,027	7.93%
	23	Chemical engineering	9,964	7.16%
	29	Other special machines	9,124	6.56%
	24	Handling	8,375	6.02%
	25	Manufacture of electronic components and boards	7,655	5.50%
	32	Transport	5,685	4.09%
	15	Biotechnology	5,538	3.98%
	6	Computer technology	5,427	3.90%
	9	Optics	5,095	3.66%

GRINS – Growing Resilient, Inclusive and Sustainable

“9. Economic and financial sustainability of systems and territories”

Codice identificativo: PE00000018

	28	Textile and paper machines	4,978	3.58%
Reuse	29	Other special machines	14,714	10.14%
	25	Manufacture of electronic components and boards	8,15	5.62%
	19	Basic materials chemistry	8,081	5.57%
	20	Materials, metallurgy	8,081	5.57%
	15	Biotechnology	7,798	5.38%
	28	Textile and paper machines	7,563	5.21%
	23	Chemical engineering	7,226	4.98%
	1	Electrical machinery, apparatus, energy	7,193	4.96%
	21	Surface technology, coating	5,895	4.06%
	17	Macromolecular chemistry, polymers	5,515	3.80%
Recycle	29	Other special machines	6,962	8.86%
	32	Transport	5,922	7.54%
	31	Mechanical elements	5,092	6.48%
	1	Electrical machinery, apparatus, energy	5,029	6.40%
	25	Manufacture of electronic components and boards	4,592	5.85%
	35	Civil engineering	4,35	5.54%
	34	Other consumer goods	3,144	4.00%
	26	Machine tools	3	3.82%
	28	Textile and paper machines	2,683	3.42%
	33	Furniture, games	2,669	3.40%
Repair	24	Handling	6,303	17.65%
	1	Electrical machinery, apparatus, energy	4,222	11.83%
	23	Chemical engineering	3,755	10.52%
	29	Other special machines	2,575	7.21%
	19	Basic materials chemistry	2,01	5.63%
	20	Materials, metallurgy	1,812	5.08%
	25	Handling	1,749	4.90%
	8	Semiconductors	1,472	4.12%
	33	Furniture, games	1,292	3.62%
	35	Civil engineering	1,248	3.50%
Refurbish	35	Civil engineering	3,223	10.40%
	29	Other special machines	3,211	10.36%
	21	Surface technology, coating	2,406	7.76%
	32	Transport	1,898	6.12%
	20	Materials, metallurgy	1,738	5.61%
	33	Furniture, games	1,525	4.92%

	25	Manufacture of electronic components and boards	1,444	4.66%
	8	Semiconductors	1,334	4.30%
	34	Other consumer goods	1,246	4.02%
	28	Textile and paper machines	1,123	3.62%

Table A 10. Distribution of patents per 5R topics across IPC technological fields.

Topic	Tech. Field	Name	n. patents	% patents
Material and Process Innovation	25	Handling	8,984	10.70%
	29	Other special machines	6,249	7.44%
	23	Chemical engineering	5,961	7.10%
	28	Textile and paper machines	4,767	5.68%
	33	Furniture, games	4,11	4.89%
	1	Electrical machinery, apparatus, energy	3,982	4.74%
	24	Environmental technology	3,684	4.39%
	8	Semiconductors	3,638	4.33%
	35	Civil engineering	3,119	3.71%
	32.0	Transport	3,032	3.61%
Polymers, Composites, and Material Recycling	29.0	Other special machines	10,365	13.26%
	15.0	Biotechnology	8,308	10.63%
	17.0	Macromolecular chemistry, polymers	5,94	7.60%
	19.0	Basic materials chemistry	5,792	7.41%
	28.0	Textile and paper machines	5,318	6.80%
	21.0	Surface technology, coating	4,498	5.75%
	18.0	Civil engineering	4,029	5.15%
	23.0	Chemical engineering	3,938	5.04%
	25.0	Handling	3,9	4.99%
	20.0	Basic communication processes	2,617	3.35%
Imaging and Display Technologies	9	Optics	6,053	17.82%
	8	Semiconductors	3,07	9.04%
	2	Audio-visual technology	2,77	8.15%
	6	Computer technology	2,211	6.51%
	1	Electrical machinery, apparatus, energy	2,108	6.21%
	29	Other special machines	1,655	4.87%
	10	Measurement	1,492	4.39%
	17	Macromolecular chemistry, polymers	1,348	3.97%

Adaptive Structures and Materials	21	Surface technology, coating	1,222	3.60%
	3	Telecommunications	1,025	3.02%
	29	Other special machines	9,228	10.01%
	32	Transport	7,325	7.95%
	35	Civil engineering	7,287	7.91%
	34	Other consumer goods	6,864	7.45%
	1	Electrical machinery, apparatus, energy	6,164	6.69%
	25	Handling	5,469	5.93%
	33	Furniture, games	5,042	5.47%
	31	Mechanical elements	4,655	5.05%
	26.0	Machine tools	4,329	4.70%
Agriculture and Resource Optimization	28	Textile and paper machines	3,487	3.78%
	19	Basic materials chemistry	1,493	18.53%
	15	Biotechnology	1,343	16.67%
	29	Other special machines	910	11.29%
	18	Civil engineering	781	9.69%
	24	Environmental technology	592	7.35%
	25	Handling	5,469	5.93%
	33	Furniture, games	5,042	5.47%
	31	Mechanical elements	4,655	5.05%
	26	Machine tools	4,329	4.70%
Data Communication and Digital Systems	28	Textile and paper machines	3,487	3.78%
	6	Computer technology	4,677	18.21%
	1	Electrical machinery, apparatus, energy	2,195	8.54%
	7	IT methods for management	2,089	8.13%
	4	Digital communication	2,073	8.07%
	3	Telecommunications	1,818	7.08%
	12	Control	1,418	5.52%
	10	Measurement	1,311	5.10%
	2	Audio-visual technology	1,23	4.79%
	32	Transport	1,225	4.77%
Resource and Material Efficiency	29	Other special machines	883	3.44%
	20	Materials, metallurgy	5,073	17.31%
	35	Civil engineering	1,742	9.38%
	29	Other special machines	1,481	7.97%
	19	Basic materials chemistry	1,241	6.68%
	1	Electrical machinery, apparatus, energy	932	5.02%
	24	Materials, metallurgy	870	4.68%
	2	Audio-visual technology	802	4.32%
	23	Chemical engineering	766	4.12%
	21	Surface technology, coating	743	4.00%

	17	Macromolecular chemistry, polymers	657	3.54%
Resource Recovery	24	Environmental technology	9,435	15.21%
	23	Chemical engineering	4,901	13.10%
	19	Basic materials chemistry	1,933	5.17%
	15	Biotechnology	1,781	4.76%
	29	Other special machines	1,738	4.64%
	35	Civil engineering	1,628	4.35%
	25	Handling	1,477	3.95%
	1	Electrical machinery, apparatus, energy	1,35	3.61%
	30	Thermal processes and apparatus	1,308	3.50%
	33	Furniture, games	1,062	2.84%
Battery Technologies and Recycling	1	Electrical machinery, apparatus, energy	8,525	14.71%
	20	Materials, metallurgy	1,694	8.88%
	32	Transport	1,198	6.28%
	8	Semiconductors	848	4.45%
	21	Surface technology, coating	837	4.39%
	23	Chemical engineering	620	3.25%
	25	Handling	468	2.45%
	29	Other special machines	434	2.28%
	28	Textile and paper machines	417	2.19%
	24	Environmental technology	404	2.12%
Recycling Equipment and Waste Management	23	Chemical engineering	4,542	14.06%
	29	Other special machines	3,643	11.28%
	24	Environmental technology	3,314	10.26%
	26	Machine tools	2,068	6.40%
	25	Handling	1,634	5.06%
	20	Materials, metallurgy	1,532	4.74%
	19	Basic materials chemistry	1,364	4.22%
	35	Civil engineering	1,3	4.02%
	1	Electrical machinery, apparatus, energy	1,224	3.79%
	31	Mechanical elements	1,119	3.46%

Table A 11. Distribution of patents per CE topics across IPC technological fields.

Topic	Company Name	n. patents	% patents
Reduce	Samsung Electronics Co., Ltd.	1,217	0.87%
	Matsushita Electric Industrial Co., Ltd.	839	0.60%

	LG Electronics	642	0.46%
	Hewlett Packard Development Company	607	0.43%
	Robert Bosch GmbH	542	0.39%
	General Electric Co.	536	0.38%
	E.I. du Pont de Nemours and Company	492	0.35%
	Siemens AG	474	0.34%
	Toyota Jidosha CO. Ltd.	462	0.33%
	Procter & Gamble	459	0.33%
Reuse	Hewlett Packard Development Company, L.P.	1,172	0.81%
	Procter & Gamble	1,066	0.73%
	LG Chem Ltd.	645	0.44%
	E.I. du Pont de Nemours and Company	624	0.43%
	Novozymes A/S	594	0.41%
	Samsung Electronics Co., Ltd.	584	0.40%
	3M Innovative Properties Co.	540	0.37%
	BASF SE	534	0.37%
	Matsushita Electric Industrial Co., Ltd.	476	0.33%
	General Electric Co.	446	0.31%
Recycle	Siemens AG	572	0.72%
	General Electric Co.	470	0.59%
	Samsung Electronics Co., Ltd.	433	0.54%
	Robert Bosch GmbH	415	0.52%
	The Boeing Co.	394	0.50%
	LG Electronics	377	0.47%
	Bayerische Motoren Werke AG	367	0.46%
	E.I. du Pont de Nemours and Company	288	0.36%
	Hewlett Packard Development Company, L.P.	260	0.33%
	Halliburton Energy Services Inc.	254	0.32%
Repair	Samsung Electronics Co., Ltd.	299	0.83%
	LG Chem Ltd.	208	0.58%
	Robert Bosch GmbH	186	0.52%
	LG Electronics	167	0.47%
	Matsushita Electric Industrial Co., Ltd.	157	0.44%
	Voith Patent GmbH	125	0.35%
	Procter & Gamble	123	0.34%
	SANYO Electric Co., Ltd.	120	0.33%
	Siemens AG	117	0.33%
	BASF SE	91	0.25%

Refurbish	The Boeing Co.	225	0.71%
	General Electric Co.	177	0.56%
	3M Innovative Properties Co.	142	0.45%
	E.I. du Pont de Nemours and Company	136	0.43%
	Procter & Gamble	125	0.40%
	Siemens AG	112	0.35%
	Airbus Operations GmbH	97	0.31%
	Hewlett Packard Development Company, L.P.	92	0.29%
	Hoechst AG	85	0.27%
	SCHOTT AG	82	0.26%

Table A 12. Top applicants by 5R topics.

Topic	Company Name	n. patents	% patents
Material and Process Innovation	Hewlett Packard Dev Co LP	562	0.67%
	LG Electronics Inc	557	0.67%
	The Procter & Gamble Co	459	0.55%
	Samsung Electronics Co Ltd	412	0.49%
	Matsushita Electric Ind Co Ltd	395	0.47%
	Voith Patent GmbH	292	0.35%
	The Boeing Co	279	0.33%
	Siemens Ag	278	0.33%
	Robert Bosch GmbH	273	0.33%
	E I Du Pont De Nemours & Co	255	0.31%
Polymers, Composites, and Material Recycling	Novozymes As	728	0.95%
	The Procter & Gamble Co	649	0.85%
	E I Du Pont De Nemours & Co	641	0.83%
	BASF SE	464	0.60%
	BASF AG	404	0.53%
	Voith Patent GmbH	377	0.49%
	Dsm IP Assets BV	314	0.41%
	The Regents Of The University Of California	300	0.39%
	Henkel AG&Co KGaA	291	0.38%
	Bayer AG	268	0.35%
Imaging and Display Technologies	Samsung Electronics Co Ltd	510	1.48%
	Matsushita Electric Ind Co Ltd	280	0.81%
	3M Innovative Properties Co	265	0.77%
	Fujifilm Corp	249	0.72%
	Eastman Kodak Co	242	0.70%

	Canon Co Ltd	231	0.67%
	Apple Inc	193	0.56%
	LG Electronics Inc	179	0.52%
	Kon Philips Elect Nv	171	0.50%
	Halliburton Energy Services Inc	160	0.47%
Adaptive Structures and Materials	Hewlett Packard Dev Co LP	896	0.94%
	Samsung Electronics Co Ltd	681	0.71%
	General Elect Co	638	0.67%
	Nike Inc	523	0.55%
	Siemens Ag	483	0.51%
	The Boeing Co	427	0.45%
	Robert Bosch Gmbh	410	0.43%
	LG Electronics Inc	392	0.41%
	The Procter & Gamble Co	360	0.38%
	United Tech Corp	298	0.31%
Agriculture and Resource Optimization	E I Du Pont De Nemours & Co	75	0.94%
	Novozymes As	58	0.73%
	Basf Ag	56	0.70%
	Varco I P Inc	56	0.70%
	Dsm Ip Assets Bv	49	0.61%
	Fujifilm Corp	40	0.50%
	The Regents Of The University Of California	30	0.38%
	Michelin Recherche Et Technique Sa	27	0.34%
	Farmer, Sean	26	0.33%
	Murata Manufacturing Co Ltd	26	0.33%
Data Communication and Digital Systems	Samsung Electronics Co Ltd	291	1.14%
	Hewlett Packard Dev Co LP	255	1.00%
	Apple Inc	213	0.84%
	Siemens Ag	185	0.73%
	General Elect Co	181	0.71%
	Sony Corp	158	0.62%
	Robert Bosch Gmbh	140	0.55%
	Matsushita Electric Ind Co Ltd	133	0.52%
	Toyota Jidosha Co Ltd	123	0.48%
	Silverbrook Research Pty Ltd	122	0.48%
Resource and Material Efficiency	Halliburton Energy Services Inc	177	0.94%
	Ajinomoto Co Inc	102	0.54%
	Sika Tech Ag	88	0.47%
	United States Gypsum Co	81	0.43%
	Basf Se	78	0.41%
	Construction Research & Tech Gmbh	75	0.40%

	3M Innovative Properties Co	70	0.37%
	Siemens Ag	61	0.32%
	Matsushita Electric Ind Co Ltd	57	0.30%
	Degussa Ag	54	0.29%
Resource Recovery	Samsung Electronics Co Ltd	139	0.38%
	Robert Bosch Gmbh	135	0.37%
	LG Chem Ltd	122	0.33%
	Siemens Ag	112	0.30%
	The Procter & Gamble Co	110	0.30%
	General Elect Co	99	0.27%
	LG Electronics Inc	94	0.25%
	The Regents Of The University Of California	92	0.25%
	Matsushita Electric Ind Co Ltd	88	0.24%
	Degremont	85	0.23%
Battery Technologies and Recycling	LG Chem Ltd	517	2.56%
	Matsushita Electric Ind Co Ltd	306	1.52%
	Samsung Electronics Co Ltd	271	1.34%
	Robert Bosch Gmbh	261	1.29%
	Toyota Jidosha Co Ltd	241	1.20%
	Contemporary Amperex Tech Co Ltd	131	0.65%
	Murata Manufacturing Co Ltd	122	0.61%
	Siemens Ag	114	0.57%
	Sanyo Elect Co Ltd	113	0.56%
	Basf Se	107	0.53%
Recycling Equipment and Waste Management	Mann Hummel Gmbh	272	0.83%
	The Procter & Gamble Co	167	0.51%
	Siemens Ag	148	0.45%
	Deere & Co	133	0.40%
	Robert Bosch Gmbh	128	0.39%
	Ntn Corp	118	0.36%
	Cnh Industrial Belgium Nv	108	0.33%
	Matsushita Electric Ind Co Ltd	107	0.33%
	Samsung Electronics Co Ltd	101	0.31%
	Ab Skf	88	0.27%

Table A 13. Top applicants per CE topics.

1.5.2 Mapping CE-related scientific activities

1.5.2.1 Data sources

We use the OpenAlex (OA) database (Priem et al., 2022) to retrieve scientific publications data. OA is an extensive open-access bibliographic database launched in 2022 that includes over 260 million scientific publications, such as journal articles, book chapters, and conference proceedings. The database is fully open access and regularly updated.

Scientific publications in OA are grouped into “topics” using an automated system that analyzes information such as title, abstract, journal name, and citations. OA identifies 4516 topics; each publication can be assigned up to three topics. The topic with the highest score is the publication's “primary topic.” These topics are organized into 252 subfields, grouped into 26 fields and further combined into 4 top-level domains.

To select topics related to CE, we searched for the term “circular economy” in the titles, descriptions, and keywords of OA’s topics. We identified eight topics related to CE, which are described in Table 9.

Table 9 – List of OA’s topics related to CE

Id	Topic Name	Subfield	Field	Domain	Summary
13240	Bioeconomy and Sustainability Development	General Agricultural and Biological Sciences	Agricultural and Biological Sciences	Life Sciences	This cluster of papers explores the role of biomass and bioenergy in the bioeconomy, focusing on policies, sustainability, innovation, and the transition to a circular economy. It covers a wide range of topics including national strategies, governance, societal perceptions, industrial transformation, and the potential impact on regional development.
13180	Chemistry and	Environmental Chemistry	Environmental Science	Physical Sciences	This cluster of papers focuses on

	Chemical Engineering				the principles and applications of green chemistry, with a particular emphasis on sustainable chemistry, solvent selection, green engineering, metrics for assessing greenness, catalysis, life cycle assessment, circular economy, process mass intensity, medicinal chemistry, and environmental impact. The papers cover various aspects of incorporating green chemistry into research, development, and manufacturing processes across the pharmaceutical and chemical industries.
11091	Extraction and Separation Processes	Mechanical Engineering	Engineering	Physical Sciences	This cluster of papers focuses on the recycling of lithium-ion batteries, recovery of rare earth elements, and sustainable technology for metal recovery. It discusses hydrometallurgical processes, circular economy implications, environmental impact, and global supply concerns related to battery recycling and rare earth recovery.
13045	Industrial Engineering and Technologies	Mechanical Engineering	Engineering	Physical Sciences	This cluster of papers focuses on the intersection of digital economy,

					sustainable development, and technological innovation within the mineral resource sector. It covers topics such as energy efficiency, carbon sequestration, hydrogen initiatives, lithium-ion batteries, and renewable energy, with a specific emphasis on resource efficiency and circular economy principles.
13477	Sustainable Design and Development	Building and Construction	Engineering	Physical Sciences	This cluster of papers covers a wide range of topics related to sustainable design, urban development, and environmental management. It includes discussions on circular economy, resource recovery, green urbanism, climate change, product development, biomimicry, and social innovation.
12746	Sustainable Industrial Ecology	Industrial and Manufacturing Engineering	Engineering	Physical Sciences	This cluster of papers explores the concept of industrial symbiosis and the development of eco-industrial parks, focusing on topics such as circular economy, industrial ecology, sustainability, network analysis, waste management, urban industrial symbiosis, environmental

					assessment, and regional development. The papers cover case studies from various countries and provide insights into the potential benefits and challenges of implementing industrial symbiosis initiatives.
10539	Sustainable Supply Chain Management	Strategy and Management	Business, Management and Accounting	Social Sciences	This cluster of papers explores the conceptualization and implementation of the circular economy, with a focus on sustainable supply chain management, green practices, supply chain network design, remanufacturing, and business model innovation. It emphasizes the integration of environmental management and resource efficiency into product design and supply chain operations to achieve triple bottom line sustainability.
11672	Utilization of Waste Materials in Construction and Ceramics	Building and Construction	Engineering	Physical Sciences	This cluster of papers focuses on the utilization of various waste materials, such as incineration residues, sewage sludge ash, and glass-ceramics, in the production of bricks and ceramic materials. It explores the recycling and sustainable use of these waste

					materials, as well as their leaching behavior and potential applications in promoting a circular economy.
Notes: The full list of topics with their associated subfields, fields, and domains is available from OA's technical documentation (see: https://docs.openalex.org/api-entities/topics , last visited in December 2024).					

In this way, we collected all international scientific articles – defined as articles published in English in international scientific journals – associated with at least one of the CE-related topics, and in which at least one author is affiliated with an institution based in Italy, covering the period from 1995 to 2024. The total number of such publications is 9,080.³

1.5.2.2 Exploratory analysis

1.5.2.2.1 Topic distribution

Figure 11 shows the share of articles across eight OA topics related to the CE. Most of these topics belong to the Physical Sciences, except for two. “Bioeconomy and Sustainable Development,” which falls under Life Sciences, accounts for 4.6% of CE publications. “Sustainable Supply Chain Management,” classified under Social Sciences, has the largest share at almost 42%.

Among the remaining six topics, five belong to Engineering. Two fall under Mechanical Engineering – “Extraction and Separation Processes” and “Industrial Engineering and Technologies” – which together account for around 19%. Two belong to Building and Construction – “Utilization of Waste Materials in Construction and Ceramics” and “Sustainable Design and Development” – making up around 15%. The last topic in Engineering, “Sustainable Industrial Ecology,” represents almost 7% of CE articles.

The last topic in the Physical Sciences domain is “Chemistry and Chemical Engineering,” which falls under Environmental Sciences, specifically Environmental Chemistry, and accounts for 11.8% of CE publications.

Figure 11 – Share of articles by CE topic.

³ The total number of publications across all scientific fields in the same period is approximately 2.3 million.

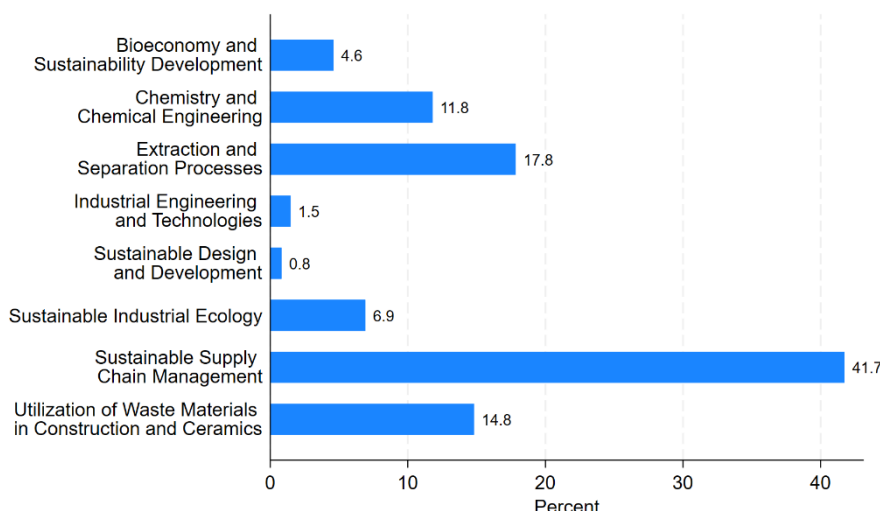


Table 10 provides an overview of the distribution of scientific articles across these topics over six distinct time windows (from 1995 to 2024). The data reveals significant trends and shifts in research focus over time, reflecting the evolving priorities and advancements within the CE domain.

Table 10 – Share of articles across CE topics by time window

Topic	1995–99	2000–04	2005–09	2010–14	2015–19	2020–24
Bioeconomy and Sustainability Development	0.4	1.0	1.9	3.5	5.8	5.3
Chemistry and Chemical Engineering	26.0	21.0	21.0	15.0	10.0	8.7
Extraction and Separation Processes	32.5	30.0	21.6	19.5	17.6	14.9
Industrial Engineering and Technologies	2.8	3.7	2.7	0.9	0.9	1.4
Sustainable Design and Development	0.8	0.0	1.3	0.9	0.7	0.8
Sustainable Industrial Ecology	4.1	2.5	5.3	5.5	7.6	7.8
Sustainable Supply Chain Management	6.1	10.9	19.4	34.8	43.7	51.2
Utilization of Waste Materials in Construction and Ceramics	27.2	30.9	26.9	19.8	13.6	9.8

We can observe from the table that topics like “Bioeconomy and Sustainability Development” and “Sustainable Supply Chain Management” show a clear upward trend, particularly from 2010 onwards. The latter, for example, increased from 6.1% in

1995–1999 to 51.2% in 2020–2024, indicating growing interest in integrating sustainability into supply chain processes as a response to global environmental challenges.

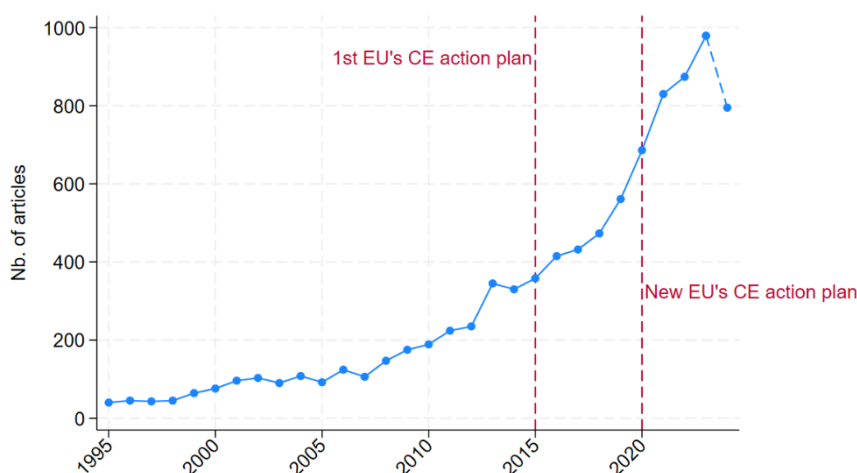
In contrast, topics such as “Extraction and Separation Processes,” “Chemistry and Chemical Engineering,” and “Recycling and utilization of industrial and municipal waste in materials production” exhibit a visible decline. In particular, the latter's share dropped from a steady share of around 27–30% in the period 1995–2009 to less than 10% in the last time window, potentially signaling a recent shift towards more innovative or diverse approaches to waste management within the CE framework.

Other fields like “Sustainable Industrial Ecology,” “Sustainable Design and Development,” and “Industrial Engineering and Technologies” demonstrate a more consistent presence over time, even with a slight increase in recent years, in the case of the first. On the other hand, the latter two fields have a negligible representation in recent time windows. This indicates that these areas are still relatively minor additions to the CE discourse. This suggests the need for more interdisciplinary approaches that integrate technological innovation, industrial processes, and ecological principles in technology, policy shifts, and global sustainability goals.

1.5.2.2.2 Time trend

Figure 12 illustrates the growth in the number of scientific articles on CE across Italy over time. Until the early 2010s, the number of articles remained relatively low, with only a modest and steady increase. This reflects the early stages of CE research in Italy, likely influenced by limited global and national focus on the topic during this period. A noticeable acceleration in the number of CE-related articles is observed around 2015, the year of the European Union's first CE Action Plan, which likely spurred research efforts in Italy, aligning national priorities with European policy objectives. Another increase is evident after 2020, correlating with the introduction of the EU's new CE Action Plan. This highlights the continued prioritization of CE within European and Italian policy frameworks, driving increased academic and industrial interest. The drop for the year 2024 is due to truncation and delays in updating publications on OA.

Figure 12 – Number of CE articles in Italy (1995–2024)



1.5.2.2.3 Geographical distribution

Figure 13 shows that the increase in CE publication volume is primarily driven by a few regions, notably Lombardy and Lazio. Their respective capitals, Milan and Rome, are the cities with the highest concentration of CE-related articles over the entire period, with nearly 1,400 articles originating from Milan and almost 1,800 from Rome (see Figure 14). The third-highest region for CE article production is Campania, located in southern Italy. Campania's surge in publications is the most recent, beginning after 2020, and it has now surpassed both Piedmont and Tuscany. Naples, the capital of Campania, ranks as the third city in CE article production over the entire period, ahead of Turin and Bologna, the capitals of Piedmont and Emilia-Romagna, respectively (see Figure 14).

Figure 13 – Number of CE articles in Italy, by NUTS 2 region (1995–2023)

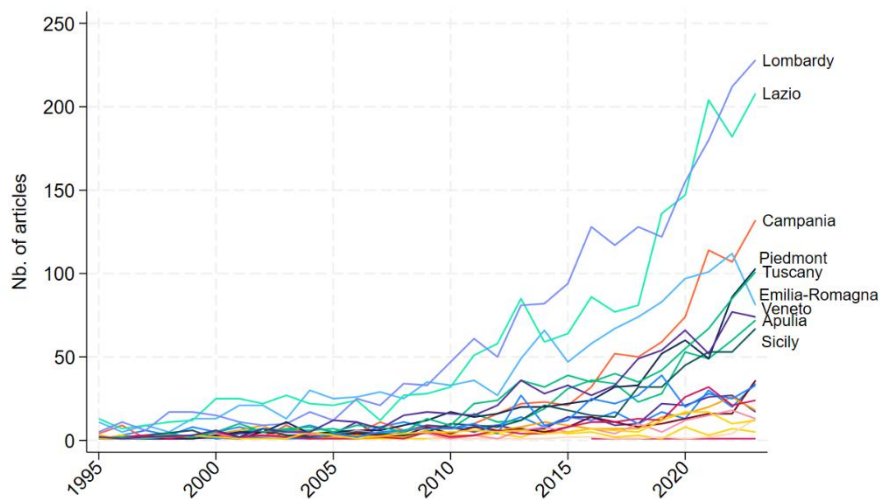


Figure 14 - Number of CE articles in Italy, top 20 cities

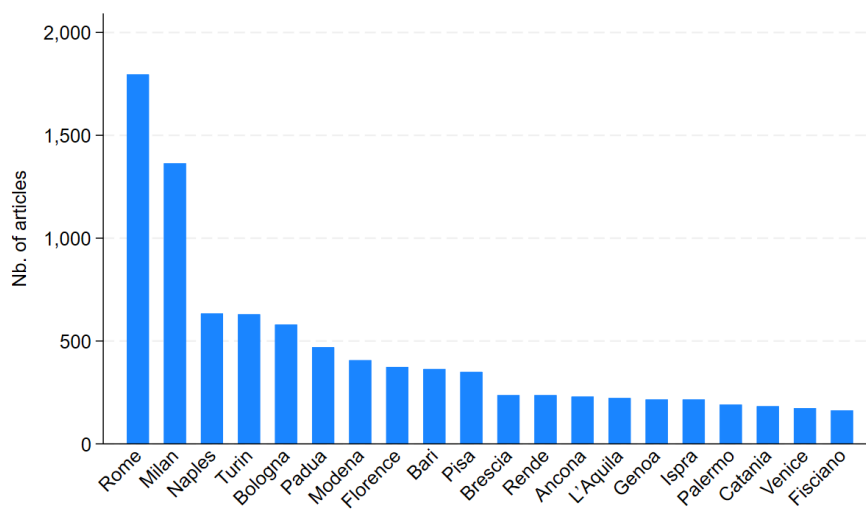


Figure 15 - Regional distribution of CE articles production

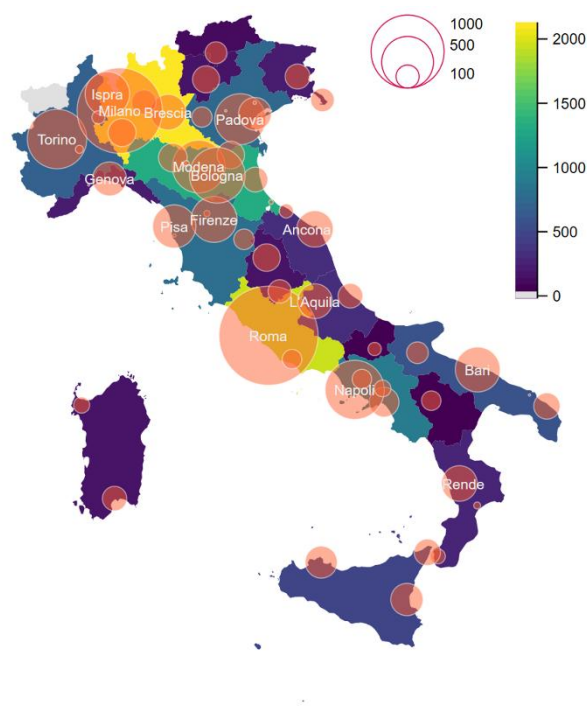


Figure 15 shows the regional distribution of circular economy (CE) articles published in Italy between 1995 and 2024. The size of the circles represents the total number of articles produced in each city (only cities with at least 10 CE articles are shown), while the color scale highlights the overall regional contribution.

At a regional level, CE articles are concentrated in a few key areas. The main contributors are Lombardy, Lazio, and Emilia-Romagna, followed by Campania to a lesser extent. Northern Italy emerges as one of the most active areas, with significant contributions from multiple cities in each region. For example, in Lombardy, Milan, Ispra, and Brescia stand out, while Emilia-Romagna benefits from the contributions of Modena and Bologna.

In contrast, in central and southern Italy, CE research is more centralized, with publications concentrated around major hubs. Rome dominates in Lazio, while Naples plays a similar role in Campania. Despite this, southern Italy and the islands still show notable participation, with cities such as Bari, Rende (home to the University of Calabria), and Cagliari contributing to the overall output.

This highlights a key difference between the north and the center-south of the country: northern regions tend to be multipolar, with several cities contributing significantly to CE research, while in the center-south, research is concentrated in a single dominant hub. Overall, the map highlights the crucial role played by

universities and research centers in metropolitan areas in advancing CE studies across Italy.

There is also significant regional variation in contributions to CE publications across the eight CE topics (see Figure 16 in Appendix). Lombardy stands out particularly in “Chemistry and Chemical Engineering,” “Sustainable Design and Development,” and “Sustainable Supply Chain Management.” Lazio, on the other hand, plays a key role in “Bioeconomy and Sustainability Development,” “Extraction and Separation Processes,” and “Industrial Engineering and Technologies.” Both of these regions are important contributors to the topic of “Sustainable Industrial Ecology,” while Emilia-Romagna is particularly prominent in “Utilization of Waste Materials in Construction and Ceramics.”

1.5.2.2.4 Main contributors

Table 11 highlights the top 20 institutions in Italy based on the number of CE publications. At the top of the ranking, Politecnico di Milano stands out as the clear leader, with 656 publications accounting for more than 6% of the total CE publications in Italy. It has more than 200 publications more than the institutions ranked second, Sapienza University of Rome and the University of Bologna, both of which have 447 publications, representing 4.26% of the total.

Table 11 – Top 20 institutions for CE articles production

	Institution name	Nb.	%
1	Politecnico di Milano	656	6.24
2	Sapienza University of Rome	447	4.26
3	University of Bologna	447	4.26
4	University of Padua	425	4.05
5	University of Modena and Reggio Emilia	346	3.29
6	Polytechnic University of Turin	331	3.15
7	University of Naples Federico II	272	2.59
8	National Research Council	236	2.25
9	Joint Research Centre	204	1.94
10	ENEA	203	1.93
11	University of Brescia	203	1.93
12	Marche Polytechnic University	179	1.70
13	University of Calabria	176	1.68

14	University of Turin	169	1.61
15	University of L'Aquila	166	1.58
16	University of Rome Tor Vergata	161	1.53
17	University of Palermo	160	1.52
18	Polytechnic University of Bari	155	1.48
19	Parthenope University of Naples	150	1.43
20	Scuola Superiore Sant'Anna	138	1.31
Notes: The number of publications is computed using full counting.			

Following these two universities, the University of Padua ranks third, also with a high volume of research output, exceeding 400 publications. The group of institutions with over 300 publications includes the University of Modena and Reggio Emilia and the Polytechnic University of Turin. Among the top 10, the University of Naples Federico II is the only institution located in southern Italy, emphasizing the north-central concentration of research in this field.

The last three positions in the top 10 are occupied by research institutions rather than universities: the National Research Council (CNR), the Joint Research Centre (JRC), and ENEA. These organizations play a fundamental role in applied research and policy development. CNR and ENEA are both based in Rome, while JRC is located in Ispra, which explains the presence of this city in Figure 14. Notably, no companies appear in this ranking, highlighting the still limited role of Italian firms in producing CE knowledge. The only exception is ENI, which plays a modest role through its research center near Milan. This center accounts for a small share, around 3%, of publications in the CE topic "Industrial Engineering and Technologies" (see Table 12 in Appendix).

Looking at the entire top 20, the ranking is dominated by institutions in northern and central Italy, with only a few representatives from the south, such as the University of Calabria and the University of Palermo. However, their presence highlights that CE research is gaining relevance across the country, even in regions traditionally less involved in high-volume academic publishing.

1.5.2.2.5 Appendix

Table 12 - Top 10 institutions for CE articles production, by CE topic

	Topic	Institution	Nb.	%
1	Bioeconomy and Sustainability Development	Sapienza University of Rome	31	6.09
2		University of Bologna	28	5.50
3		Joint Research Centre	27	5.30
4		Unitelma Sapienza University	24	4.72

GRINS – Growing Resilient, Inclusive and Sustainable

"9. Economic and financial sustainability of systems and territories"

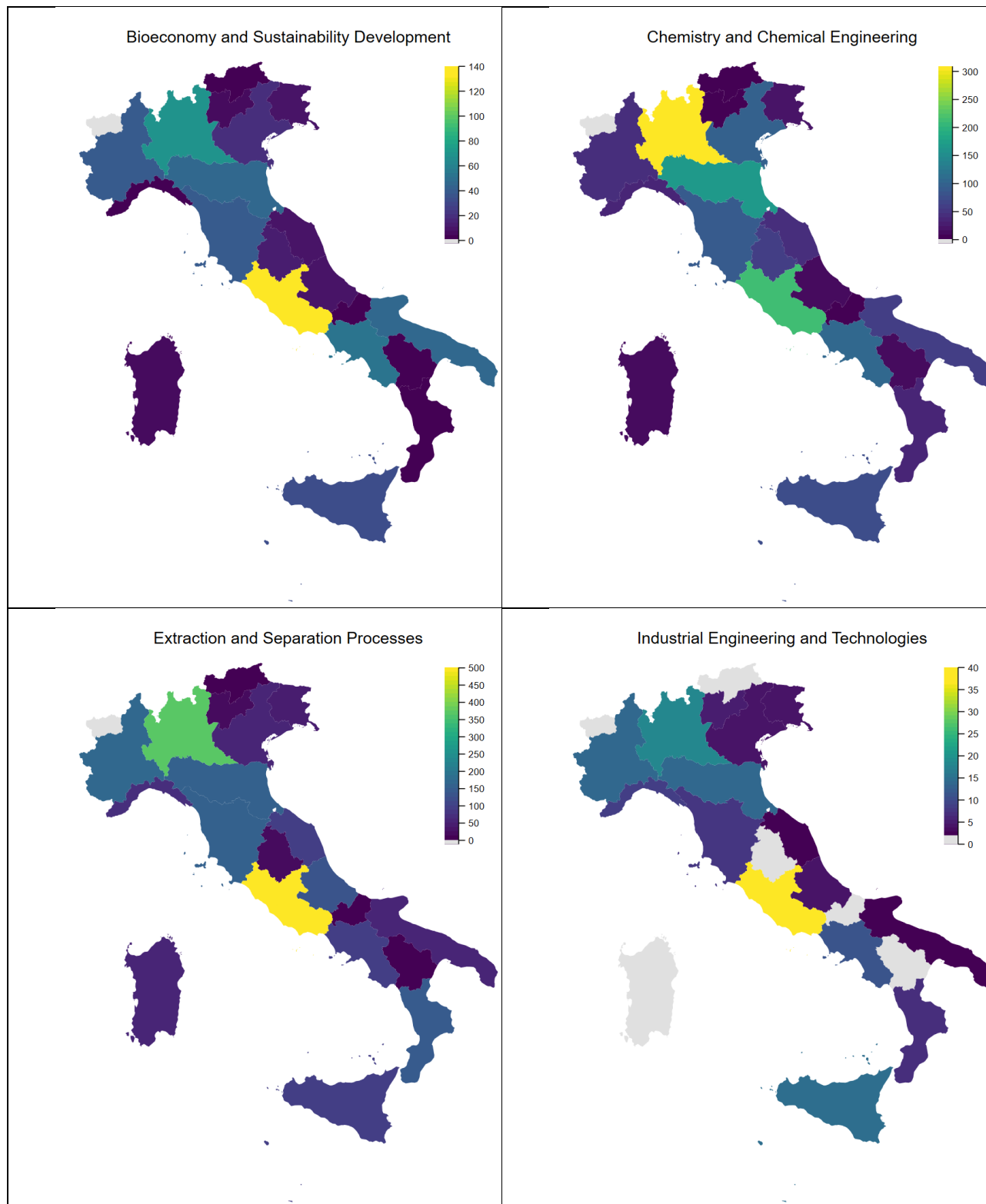
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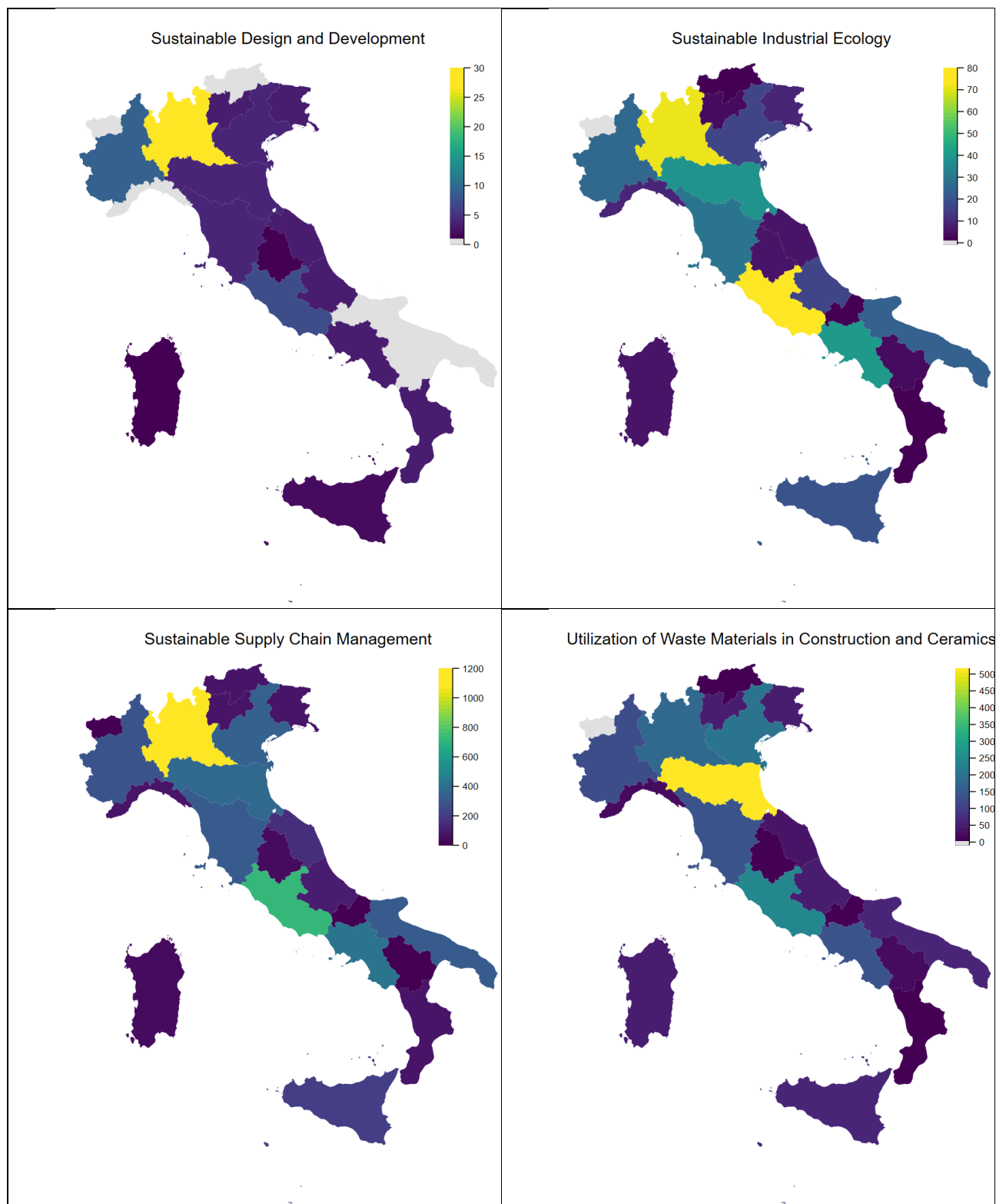
5		University of Naples Federico II	17	3.34
6		University of Foggia	16	3.14
7		National Research Council	15	2.95
8		University of Turin	15	2.95
9		University of Catania	13	2.55
10		University of Florence	13	2.55
1	Chemistry and Chemical Engineering	University of Bologna	87	6.53
2		Mario Negri Institute for Pharmacological Research	68	5.10
3		Joint Research Centre	52	3.90
4		University of Perugia	49	3.68
5		Ca' Foscari University of Venice	49	3.68
6		University of Naples Federico II	48	3.60
7		University of Milan	46	3.45
8		Sapienza University of Rome	43	3.23
9		Politecnico di Milano	36	2.70
10		IRCCS	36	2.70
1	Extraction and Separation Processes	Sapienza University of Rome	195	9.22
2		ENEA	113	5.34
3		Politecnico di Milano	112	5.30
4		University of Calabria	102	4.82
5		Polytechnic University of Turin	101	4.78
6		University of L'Aquila	94	4.44
7		Institute on Membrane Technology	81	3.83
8		University of Bologna	81	3.83
9		National Research Council	68	3.22
10		University of Pavia	51	2.41
1	Industrial Engineering and Technologies	University of Palermo	11	7.75
2		Politecnico di Milano	10	7.04
3		Polytechnic University of Turin	8	5.63
4		University of Genoa	7	4.93
5		University of Calabria	6	4.23
6		Sapienza University of Rome	6	4.23
7		University of Bologna	6	4.23
8		Eni (Italy)	5	3.52
9		University of Naples Federico II	5	3.52
10		University of Florence	4	2.82
1	Sustainable Design and Development	Politecnico di Milano	23	33.82
2		Polytechnic University of Turin	9	13.24

3		University of Chieti-Pescara	3	4.41
4		University of Reggio Calabria	3	4.41
5		University of Bologna	3	4.41
6		University of Trento	3	4.41
7		Sapienza University of Rome	2	2.94
8		Roma Tre University	2	2.94
9		Università di Camerino	1	1.47
10		University of Campania "Luigi Vanvitelli"	1	1.47
1	Sustainable Industrial Ecology	Politecnico di Milano	22	5.99
2		Sapienza University of Rome	20	5.45
3		ENEA	19	5.18
4		Polytechnic University of Turin	17	4.63
5		Polytechnic University of Bari	17	4.63
6		Parthenope University of Naples	15	4.09
7		University of Bologna	15	4.09
8		University of Chieti-Pescara	14	3.81
9		Scuola Superiore Sant'Anna	11	3.00
10		University of Modena and Reggio Emilia	11	3.00
1	Sustainable Supply Chain Management	Politecnico di Milano	410	9.46
2		University of Padua	195	4.50
3		University of Bologna	149	3.44
4		Sapienza University of Rome	143	3.30
5		Polytechnic University of Bari	130	3.00
6		University of Brescia	115	2.65
7		University of Naples Federico II	113	2.61
8		Scuola Superiore Sant'Anna	113	2.61
9		University of Rome Tor Vergata	110	2.54
10		Polytechnic University of Turin	108	2.49
1	Utilization of Waste Materials in Construction and Ceramics	University of Modena and Reggio Emilia	259	14.33
2		University of Padua	151	8.35
3		Institute of Science and Technology for Ceramics	103	5.70
4		University of Bologna	80	4.42
5		Polytechnic University of Turin	66	3.65
6		National Research Council	62	3.43
7		Sapienza University of Rome	60	3.32
8		University of Naples Federico II	51	2.82

9		University of Brescia	48	2.65
10		Politecnico di Milano	42	2.32

Figure 16 - Regional distribution of CE articles production, by CE topic





1.6 Family involvement in innovative SMEs that invest in the CE transition

1.6.1 Introduction

The circular economy (CE) has become essential for the survival of businesses and significantly affects human welfare. Discussions regarding the unsustainability of the linear model of production, consumption, and disposal have been documented for quite some time, with one notable article by Frosch & Gallopoulos (1989) from the 20th century highlighting this issue. As stated by Korhonen et al. (2018), the circular economy can be understood as a component of sustainability that aims to achieve goals across the three sustainability dimensions. The social objective of CE is to encourage a sharing economy, generate employment, foster democratic decision-making, and optimize resource utilization through community collaboration rather than individual consumption. The environmental aim is to reduce resource consumption, waste, and emissions by recycling materials and harnessing renewable energy. Finally, the economic goal of CE is to decrease costs related to materials, energy, and waste management, mitigate regulatory risks, enhance public perception, and develop new products and market opportunities. There are significant advantages to adopting a circular approach (Schroeder et al., 2019), reinforcing the importance of fostering a transition toward a circular economy that prioritizes minimizing resource inputs and waste outputs in the production-consumption cycle through material recycling and renewable energy utilization. Transitioning to a circular economy is vital for tackling global sustainability issues by moving away from a linear economic model characterized by a 'take-make-dispose' mentality, towards a regenerative system that reduces waste and optimizes resource efficiency (Urbinati et al., 2017). One aspect of this paradigm shift is the implementation of policies and practices along the entire value chain, while an essential aspect is innovation for the circular economy transition (Tan & Cha, 2021; Prieto-Sandoval et al., 2018). Circular economy innovations are therefore innovations that enable the shift from a linear economy to a circular one, aiming to reduce waste, extend the lifecycle of products, and create value from materials that would otherwise be discarded. These innovations often emerge in response to increasing consumer demand for sustainability, regulatory pressure, and above all the vast new economic opportunities generated (Tan & Cha, 2021).

The transition to CE depends on the involvement of policymakers, businesses, and individuals willing to realize the potential of CE. The numerous contributions of small

and medium-sized enterprises (SMEs) in different performance metrics highlighted in the annual report on European SMEs (Katsinis et al., 2024), position them as businesses that play a crucial role in this transition, with the European Union (EU) aiming to lead in CE. SMEs are businesses that fit a specific size range based on the number of employees, revenues, or assets. As defined by the European Union (European Commission, 2003), SMEs have fewer than 250 employees and either a turnover not exceeding 50 million euros or a balance sheet not exceeding 43 million euros. SMEs function within various strategic frameworks, influenced by a mix of financial targets, focus on internal and short-term planning, long-term sustainability aspirations, and commitments to development (Ates et al., 2013). Their operations are motivated not only by market trends and regulatory demands but also by the core values and aspirations of their owner-managers, which play a significant role in their participation in non-financial activities (Jansson et al., 2017). While some focus on financial success and competitive positioning in the market, others may be steered by long-term sustainability objectives or responsibilities to future generations. These strategic orientations are often shaped by the company's ownership and governance models, which dictate how decisions are made, and which priorities are highlighted. The ownership and governance structures can be classified into categories such as institutional, governmental, familial, foreign, managerial, and concentrated ownership structures (Elvin & Hamid, 2016, p. 105). This research examines the family ownership structure, distinguishing between family-owned and nonfamily-owned SMEs. A family-owned business is characterised by the active involvement of family members in corporate governance and key decision-making processes through the exercise of voting rights, to pursue the vision of the business in a way that benefits both the current and future generations of the family (Bendig et al., 2020; Chua et al., 1999). Family-owned businesses often focus on nonfinancial goals such as sustainability and transitioning to a circular economy (Zellweger et al., 2013), which can be achieved through innovations.

The innovation capabilities of SMEs, particularly regarding the role of family involvement, yield mixed results in existing research. Some studies indicate that family-owned firms tend to be more conservative with their innovation investments due to a preference for risk aversion, a focus on long-term stability, and concerns about preserving family control (Chirico et al., 2020; De Massis et al., 2015). Conversely, some argue that family businesses leverage their strong commitment to sustainability and intergenerational responsibility to foster innovation (Matzler et al., 2015). These opposing viewpoints underscore the intricacies surrounding family involvement in innovation practices. This situation presents an opportunity to explore the innovation strategies of family-owned enterprises in comparison to their non-

family counterparts regarding circular innovation. In light of this, the aim of this study is to establish an indicator that assesses family involvement in SMEs that are dedicated to the circular economy. This indicator emphasizes the connection and impact of family participation in a business, its influence on innovation, and the company's transition to circular economy practices through innovation, particularly within SMEs. It proposes that the engagement of family members in business decision-making significantly affects how the company approaches innovation and shifts towards more sustainable circular economy frameworks.

To examine family involvement and investment in the circular economy (CE) transition, we intend to evaluate the index following the identification of family-owned firms within the sample and the assessment of circular economy innovations through patent data.

The index⁴ used:

Circular Economy Patent Filing Rate in family versus non-family innovative SMEs:

This index measures the pace at which family-owned SMEs are filing new circular economy patents over time. It is calculated by dividing the number of circular economy patents filed by family-owned versus nonfamily-owned firms each year by the total number of years observed.

1.6.2 The role of family involvement in innovative SMEs that invest in the CE transition

1.6.2.1 Data Collection Strategy

To investigate the objective of this study, we adopted the following data collection approach:

Sample Selection

The sample is composed of innovative SMEs from Italy ("PMI innovative"), sourced from the national business registry. Innovative SMEs are defined according to Article

⁴ Note: The indicator is novel and is currently in the development stage, with no prior use in existing literature.

4 of Legislative Decree 3/2015, which established a legal framework aimed at fostering innovation-driven SMEs in Italy. Companies are categorized as either family-owned or nonfamily-owned SMEs, with family involvement being characterized by the active participation of family members in decision-making processes, including voting rights and ownership stakes (Bendig et al., 2020).

Family Involvement Identification

Family-owned firms are identified using shareholding information from the AIDA database, which offers detailed insights into ownership structures. A binary variable is employed to signify family involvement. This variable is set to 1 if family members hold at least 25% of the shares, and 0 otherwise (European Commission, 2025). To determine whether shareholders are family members, we examine the surnames of the individuals, identifying instances where two or more shareholders share the same surname. Initial statistics indicate that approximately 25% of innovative SMEs in the sample have family members owning shares in the business. Some SMEs have multiple families identified with decision making right, as reflected in the data.

Patent Data Collection

Patent information is utilized as a measure of innovation (Matzler et al., 2015; Ponta et al., 2021) and can serve to assess innovation within the context of the circular economy (Valero-Gil & Scarpellini, 2024). To analyse investment in the transition to a circular economy, we will examine patent applications from a selection of innovative SMEs and conduct content analysis to pinpoint innovations that align with circular economy principles. Patent data for our sample of innovative SMEs is obtained from PATSTAT, a comprehensive global patent database (Espacenet Patent Search, 2024). The dataset comprises 2,829 patent applications from innovative SMEs, which will be scrutinized to evaluate their alignment with circular economy principles. To identify CE-related patents, we will employ a keyword-based search framework, using methodologies synthesized from Portillo-Tarragona et al. (2022), Jose et al. (2017) and section 2 of [Deliverable 1](#).

1.6.2.2 Index Construction and Analysis

We construct an index to assess family involvement and investment in the CE transition.

A content-based analysis is performed on patent applications to classify innovations based on circular economy criteria. These classification criteria are based on green

patent categories identified using IPC classification (Portillo-Tarragona et al., 2022; Marín-Vinuesa et al., 2023) and the circularity strategy in innovation (Potting et al., 2017, p. 5). Circular patents are identified not only through IPC classification but also by analysing patent descriptions that align with the circularity strategy in Potting et al.'s (2017). The classification approach is highlighted in the table below. The number of CE-related patent applications will be identified following the categorisation. Subsequently, statistical methods will be used to compare CE patent filing rates between family-owned and nonfamily-owned SMEs over time.

Circular Patent	IPC Classification for Green and Circular Patent	Y02T10/00 – Road transport of goods or passengers Y02E60/00 – Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation Y02P10/00 – Technologies related to metal processing Y02E30/00 – Energy generation of nuclear origin Y02E10/00 – Energy generation through renewable energy sources Y02W30/00 – Technologies for solid waste management Y02W10/00 – Technologies for wastewater treatment Y02E50/00 – Technologies for the production of fuel of non-fossil origin Y02W 30/00 – Reuse, recycling, or recovery of materials Y02W 90/10 – Waste processing technologies with reduced environmental impact B09B 3/00 – Recycling and reuse of waste materials B09B 5/00 – Techniques for minimizing waste generation C08J 11/00 – Recovery and reuse of plastics C08J 3/22 – Processing of plastic waste D21B 1/00 – Reuse of paper waste
	Circularity Strategy in innovation (Potting et al. (2017))	Smarter Product Management – Refuse, Rethink, Reduce Extend the lifespan of product and its parts – Re-use, Repair, Refurbish, Remanufacture, Repurpose Useful application of material (material recycle and energy recovery) – Recycle, Recover

Circular innovation classification criteria

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1.7 Equity crowdfunding and CE scores

1.7.1 Implementing CE scores in Equity Crowdfunding literature

The indicator has been used in the paper “Sustainable crowdfunding and cultural contexts: Evidence from a longitudinal multi-country analysis,” by Luca Farè, Michele Meoli, and Silvio Vismara, published in Finance Research Letters (Farè et al., 2024). The findings of the paper show that equity crowdfunding platforms with a sustainability orientation tend to achieve better performance compared to their counterparts. The analysis, based on a longitudinal dataset of 573 equity crowdfunding platforms across 37 OECD countries from 2008 to 2023, documents that platforms incorporating sustainability criteria in the selection of ventures attract a larger number of investors and list a larger number of successful campaigns. The benefits derived from the platform sustainability orientation are negatively moderated by cultural contexts characterized by high levels of individualism and masculinity. This suggests that cultural context plays a crucial role in determining the effectiveness of sustainability strategies adopted by equity crowdfunding platforms. The study contributes to the literature on fintech, equity crowdfunding, and sustainability, providing practical implications for platform managers, investors, and policymakers interested in promoting sustainable finance.

From the dataset used in the paper, we developed an aggregate scoring system to evaluate the sustainability orientation of Italian equity crowdfunding platforms at the regional level. We use data from the CONSOB registry to track platform activity from their launch until December 31, 2023. Information on the sustainability criteria incorporated by platforms into the selection processes of firms seeking funding was collected from platform websites and reports. Based on the Morgan Stanley Capital International ESG Intangible Value Assessment (MSCI ESG IVA), the sustainability criteria were categorized into environmental (circular economy, climate change, environmental opportunities, natural resources, pollution and waste), social (human capital, product liability, social opportunities, stakeholder opposition), and governance (board of directors, business ethics, financial stability, ownership and governance) dimensions. Each platform received a score based on the total number of sustainability criteria considered. The regional sustainability orientation score was calculated as the average score of all equity crowdfunding platforms operating within each region.

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2. Case studies on CE Innovation

2.1 The role of Digital Platform and Ecosystem for the Circular Economy

2.1.1 Introduction

Circular economy has been proposed as a strategic approach, embedding closed-loop thinking at the core of businesses, industrial organizations, and national agendas (Patwa et al. 2021). As a regenerative business model, the circular economy seeks to keep products in circulation for as long as possible, enabling the recovery parts and materials at the end of their life cycle and creating additional value (Ghisellini et al., 2016). Despite the importance of this topic, several limitations impede the implementation of circular economy principles. Kirchherr et al. (2017), identified technological and financial barriers among these limitations. Furthermore, the lack of knowledge and skills necessary to support the transition from a linear to a circular economy is another significant challenge (Kumar and Malegeant, 2006; Guldmann and Huulgaard, 2020).

To address these limitations, several studies have emphasized the importance of stakeholder collaborations in fostering innovation for the circular economy. Rajala et al. (2018) highlighted that the presence of an ecosystem and collaboration among different actors are essential for a closed-loop economy to thrive, enabling the sharing of resources and skills. According to Konietzko et al. (2020), ecosystems play a fundamental role in advancing the implementation of the circular economy by enabling collaboration among companies and other organizations to drive innovation towards circularity. Participation in ecosystems can help mitigate resource and skill shortages, facilitating the adoption of circular economy practices through the development of dense networks of relationships that enhances knowledge transfer and innovation (Oksanen and Hautamäki, 2015; de Vasconcelos Gomes et al., 2023). Thus, it is crucial for businesses to engage and collaborate with diverse stakeholders, including public institutions, universities, research institutes, and end users of their products and services (Zeng et al., 2022).

Networks, such as digital platforms, are recognized as valuable sources of information, while a fertile ecosystem can serve as a catalyst for the adoption of

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“9. Economic and financial sustainability of systems and territories”

Codice identificativo: PE00000018

circular economy practices among firms. Digital platforms have transformed value creation within innovation ecosystems by enhancing knowledge processes (Romano et al., 2014), and fostering collaboration among actors (Yoo et al., 2012). These platforms act as infrastructures for innovation and transactions, facilitating knowledge sharing across diverse industrial resources and devices (Cenamor et al., 2017). The study of digital platforms, particularly from the circular economy perspective, is an emerging field. Schwanholz and Leipo (2020) analyzed the motivations and business models of digital sharing platforms, emphasizing the need for further investigation into their practical contributions to the circular economy. The authors suggest further exploration of the practical contributions of digital platforms to the circular economy. Therefore, this study aims to understand how digital platforms support the transition to a circular economy.

This research aims to address the following research questions:

RQ1. How can a digital platform support the transition to a Circular Economy?

RQ2. How can digital platform create a Multi-Stakeholder Network to support the transition to a Circular Economy?

2.1.2 Theoretical Background.

Research suggests that networks can surpass traditional organizational methods in creating, transferring, and recombining information and knowledge (Jordão, 2015). A firm's intellectual capital relies on the application of both tacit and explicit knowledge, which drives innovation and enhances financial performance (Nonaka and Takeuchi, 2007; Jordao and Novas, 2017). Digital platforms, defined as online systems facilitating interactions among distinct groups, are increasingly recognized for their transformative potential (Hein et al, 2020). These platforms can vary in form, with distinct characteristics and purposes (Eisenmann et al., 2006). The proliferation of digital platforms has shifted the focus of value creation from traditional linear value chains to interconnected networks (Karimi and Walter, 2015; McIntyre and Srinivasan, 2017). Digital platforms serve as infrastructures for both innovation and transaction, enabling the sharing of data across diverse industrial resources and devices (Cenamor et al., 2017). They also support market infrastructures that facilitate distribution and sharing among business partners. Moreover, these platforms can coordinate technological development and innovation through modular architectures and appropriate governance structures (Tiwana, 2013).

The network capability of digitally integrated firms relies on a shared architecture that facilitates internal and external knowledge sharing (Cenamor et al., 2017).

Digital platforms have revolutionized value creation opportunities in innovation ecosystems by significantly enhancing processes of knowledge creation, absorption, and dissemination (Romano et al., 2014). Nambisan et al. (2017) emphasized the role of digital platforms as innovation infrastructures, providing tools and resources for experimentation and the development of new ideas. These platforms foster collaboration among diverse actors, including customers, partners, and competitors, enabling the co-creation of innovative products and services (Yoo et al., 2012). Collaboration, a key driver of circular supply chains, is essential in shaping the relationships among partners within a circular economy framework (Mangla et al., 2021).

In this context, the capability of digital platforms enables companies to strengthen their communication with external partners and to more effectively acquire and organize structured information from them (Cenamor et al., 2017). Gawer and Cusumano (2014) highlighted that digital platform act as economic centers of gravity, around which products, services, and other resources revolve. These platforms act as foundational infrastructure upon which other businesses can build and innovate, fostering the development of true ecosystems. The concept of a business ecosystem refers to collectives of heterogeneous yet complementary organizations that collaborate to create value at the system level (Jacobides et al., 2018).

Innovation ecosystems are environments where interactions among actors enable firms to pool resources (Bouncken and Kraus, 2013; Pushpanathan and Elmquist, 2022; Thomas et al., 2022). These ecosystems are also recognized as institutional infrastructures that foster networking and collaboration among multiple stakeholders, facilitating intense and virtuous knowledge flows (Romano et al., 2014). Chesbrough and Appleyard (2007) emphasized the significant role of innovation ecosystems in shaping individual firms' innovation strategies. Companies are increasingly aware about the necessity of engaging in valuable networking relationships to acquire resource acquisition and drive innovation (Jørgensen and Ulhøi, 2010; Wong et al., 2019). This collaborative approach is particularly essential in scenario where innovation would be extremely challenging without the support of network partners (Konsti-Laakso et al., 2012). In summary, these insights highlight the pivotal role of networks such as digital platforms in building social capital, thereby enhancing an organization's capacity to effectively generate, share, and utilize knowledge (Lin, 2017).

2.1.3 Research Context. Italian Circular Economy Stakeholder Platform (ICESP)

In 2018, the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) established the Italian Circular Economy Stakeholder Platform (ICESP) following the creation of the European Circular Economy Stakeholder Platform (ECESP) by the European Commission in 2017.

ENEA plays a key role in disseminating knowledge and information from ECESP coordination groups to ICESP stakeholders while promoting exemplary Italian practices across Europe. ICESP is composed of a president, a technical coordinator, an ECESP liaison, a committee of working group (WG) coordinators, and an Assembly of members. The Assembly convenes annually to review past activities, plan future initiatives, review WG changes, approve the annual report, admit new members, and discuss the removal of inactive ones.

ICESP functions as a digital forum to engage stakeholders and nurture a digital innovation ecosystem for the circular economy. Its primary goals include coordinating local efforts, facilitating experience exchanges, and promoting best practices by fostering collaboration among governments, businesses, research institutions, and NGOs, aiming to showcase Italy's distinctive approach to implement the circular economy.

Membership in ICESP includes local and central public administrations, educational and research sectors, businesses, industry associations, and civil society representatives. The platform fosters dialogue and collaboration among diverse circular economy actors, promoting the adoption of circular practices through knowledge exchange, pilot projects, and dissemination of best practices. ICESP plays a vital role in mapping Italy's circular initiatives and identifying future opportunities. Its success is bolstered by the endorsement of the Italian government and the European Commission, providing legitimacy, resources, and strategic alignment with EU policies. This institutional support strengthens Italy's leadership in the European circular economy landscape. As a model of effective public-private collaboration in circular economy innovation, ICESP contributes to a sustainable future by consolidating initiative, sharing experiences, addressing critical issues, and advancing Italy's circular economy through targeted actions.

Recognized for its characteristics and institutional backing, ICESP serves as a pivotal case study of a digital ecosystem for the circular economy. It underscores Italy's

commitment to advancing circular practices with broad stakeholder engagement and innovative solutions.

2.1.4 Methodology and data collection

Case studies aim to explore and explain phenomena within their real-world context rather than quantify them, aligning well with our research objectives (Yin, 2003). This study employs the extreme case study method, which is particularly valuable for gaining insights from rare or exceptional positive or negative examples. This approach prioritizes in-depth understanding over generalizability, making it especially suitable when a random sample would be inadequate. ICESP was identified as a critical and extreme case of a digital ecosystem for circular economy due to its unique characteristics (Eisenhardt, 1989). As such, the case study approach enabled us to effectively address our research question. Data collection followed Yin's methodology (2003), which includes several steps: 1) defining research questions and objectives, 2) developing a case study protocol outlining its purpose, data collection procedures, structure of the case study report and protocol questions (including operationalising the phenomenon and formulate interview questions). Following previous studies (Yin, 2003; Gnyawali and Park, 2011; Stigliani and Ravasi, 2012), data collection proceeded in two phases. Initially, secondary data were gathered to understand the broader context of digital platforms in the circular economy. This included analyzing newspaper articles, website content, and press releases prior to conducting interviews. Subsequently, semi-structured interviews were conducted with members to gain deeper into how socially oriented ecosystems facilitate value acquisition through digital platforms.

2.1.5 Case analysis and Discussion

ICESP operates via a digital platform to facilitate the sharing of information and best practices (www.icesp.it). The platform organizes periodic consultations for Working Group (WG) and Subgroup meetings, enabling stakeholders to collaborate on various topics. Moreover, ICESP engage in activities through its WGs, addressing a range of circular economy issues. It also produces position papers, documents, and specific analyses on critical issues related to the circular economy. According to the interviewee:

"It is a free and neutral network. This neutrality has been its strength, as there are no predominant interests. This impartiality has been appreciated because it is a

platform for dialogue and discussion on the main challenges and solutions related to the implementation of the circular economy. The goal is to build a network of stakeholders to foster a high-value scientific debate, highlighting gaps, peculiarities, and potential solutions for ongoing processes”.

Thus, ICESP seeks to establish a national digital network for sharing knowledge on initiatives, experiences, challenges, prospects, and expectations related to the circular economy.

ICESP also platform includes (i) a programmatic manifesto (ICESP Charter) which outlines the initiative’s motivations, objectives, common interests, and operational tools, and (ii) regulations that govern the platform’s operations and define the roles and responsibilities of its participants. Finally, ICESP serves as knowledge hub, offering a repository of best practices to support the transition of a circular economy.

Generally, the digital platform aims to position itself as a practical tool for advancing the circular economy through three main directives:

- 1) Creating a permanent network to foster dialogue and possible synergies among Italian stakeholders.
- 2) Sharing and disseminating knowledge on the circular economy through best practices, helping stakeholders understand how to implement these practices.
- 3) Supporting policymakers in regulatory changes to facilitate the transition towards a circular economy.

Creating a stakeholder network

Grimble and Wellard (1997) argued that the creation of a multi-stakeholder platform requires the identification of stakeholders. On this point, the interviewee emphasized that:

“The circular economy requires the participation of various stakeholders who must cooperate to promote a cultural shift. The platform was developed through an inclusive process, involving a wide range of actors from public institutions to businesses, universities, and trade associations. When the platform started, there were about 18 participants; now there are about 150. Over time, not only has the number of participants increased, but so has their representation. Initially, we did not have the third sector; we then worked hard to involve them. It is a free network, and the only fee is commitment. It thrives solely on participation”.

The platform has experienced steady growth, involving diverse categories of stakeholders, which can be divided into two groups. The first group comprises 150

signatories of the ICESP Charter, currently. They are distributed as follows: a) 5.3% from institutions and central and local public administrations; b) 12.7% from citizens and the third sector; c) 22.7% from the education, research, and innovation sectors; d) 59.3% from businesses and trade associations. The second group includes participants actively engaged in WGs, currently amounting to 309 people. Their composition is as follows: a) 8.4% from institutions and central and local public administrations; b) 10.7% from citizens and the third sector; c) 19.1% from the education, research, and innovation sectors; d) 61.8% from businesses and trade associations.

Additionally, the interviewee highlighted on this point that:

"Members of the ICESP commit to actively contributing to various activities, such as participating in platform initiatives, actively joining WGs, providing and reporting best practices according to the platform's format, and promoting ICESP and its objectives through their channels".

Thus, we can affirm that ICESP functions as a network for both virtual and in-person interaction, bringing together diverse segments of society according to the quintuple helix model (Carayannis and Campbell, 2009). This model fosters dialogue among various actors to uncover perspectives, challenges barriers, and enablers for the practical implementation of the circular economy at the national level. This approach follows the evolution of the traditional triple helix model of innovation, which includes universities, industry, and government, by incorporating additional dimensions such as towards a quintuple helix model that integrates media, shared culture, civil society, and the environment (Carayannis and Campbell, 2009).

Digital platform for sharing and generation of knowledge

The circular economy represents a complex challenge that requires policy action, the involvement of diverse stakeholders, and the integration of knowledge from multiple disciplines and sectors of society (Zeng et al., 2022). Advancing circular economy practices requires cooperation and collaboration with a wide range of institutions and organizations (de Arroyabe et al., 2021; Mangla et al., 2021). Integrating the perspectives of various actors enables the identification of opportunities and challenges, facilitates dialogue and collaboration among stakeholders, and supports the sharing and interconnection of best practices, knowledge, and strategic and planning approaches. These efforts aim to foster innovation while promoting and sustaining the circular economy (Oksanen and Hautamäki, 2015). Regarding this aspect, the interviewee states:

"Participation and involvement of various stakeholders occur through WGs. The WG is fundamental because it brings together different stakeholders based on their competencies and interests".

ICESP has created six main WGs and three interdisciplinary WGs. Two or three coordinators lead each WG. These groups focus on the most relevant topics for the circular economy, addressing the main priorities and issues that require the assessment of intervention solutions.

Table 1 – ICESP – Working Groups

Group	Coordinator	Activities
1. Research and eco-innovation, dissemination of knowledge and training.	Puglia Region - ARTI (Regional Agency for Technology and Innovation), Confederation of Italian Craftsmanship and SMEs, University of Bologna	The group focuses on eco-innovation and circular economy through two subgroups. The first subgroup deals with measuring and deepening corporate eco-innovation, defining performance indicators to assess the circularity of products, services, and processes. The second subgroup identifies gaps between the skills demanded by companies and the current educational offerings, proposing policy recommendations to strengthen the technical training system.
2 Regulatory and Economic policy	National Agency for New Technologies, Energy and Sustainable Economic Development, UnionCamere	The group consists of two subgroups. The first, called "Regulatory Instruments", aims to identify regulatory tools to support the circular economy, primarily those for simplifying compliance and administrative procedures, considering the acceleration required by the National Recovery and Resilience Plan (PNRR). The second, called "Economic Instruments" aims to propose incentives to change production and consumption patterns towards greater circularity, and on the other hand, to promote and direct funding for research and innovation activities for circularity.
3. Tools for measuring the circular economy	National Agency for New Technologies, Energy and Sustainable Economic Development, Radici Group	The group conducts a national and international analysis of initiatives and indicators for measuring the circular economy.
4. Sustainable and Circular Value Chains	National Agency for New Technologies, Energy and Sustainable Economic Development, Enel, University of Turin	The group addresses the concept of closing the loop in the value chain with an integrated approach by sector. It is organized into several subgroups: construction and demolition; textiles, clothing, and fashion; electric mobility; and agri-food.
5. Circular Cities and Territories	National Agency for New Technologies, Energy and Sustainable Economic	The group gathers, analyzes, shares, and disseminates circular operational solutions implemented in cities and territories. Its aim is to provide both a national overview and to catalyze and stimulate circular transition processes in urban areas and territories.

	Development, IUAV University of Venice	
6. Best Practices and Integrated Approaches"	National Agency for New Technologies, Energy and Sustainable Economic Development, Polytechnic University of Bari, CDCA	The group gathers, analyzes, and promotes the dissemination of best practices in circular economy developed within the national territory by stakeholders committed to closing loops at every level of the value chain, aiming to achieve as comprehensive a national overview as possible of Italy's transition towards a circular economy.

The WGs convene periodically to develop reviews, technical reports, and studies, organize consultation events, and gather best practices related to the circular economy. Interdisciplinary groups oversee and align these activities, facilitating communication and coordination among the various WGs. These activities engage stakeholders and serves as platforms for exchanging ideas, solving joint problems, and provide updates on network developments (Block, 2018). Senge (2006) argued that active stakeholder involvement in decision-making is crucial for creating effective learning organizations, as it fosters commitment and contribution to the organization's success. Hackman (2002) noted that active participation in decision-making enhances team collaboration and strengthens commitment to common goals. ICESP applies these principles through its WGs, promoting an inclusive and participatory governance model. This structure fosters a collaborative network, encouraging innovative ideas and practical solutions.

Interdisciplinary WGs ensure a holistic and integrated approach, making solutions sustainable and scalable. They also promote inter-sector communication and collaboration, adopting a systemic approach to address the challenges of the circular economy. Thus, ICESP's structure and approach not only address critical circular economy issues but also create a collaborative environment that drives stakeholder engagement and innovation (Hackman, 2002; Senge, 2006).

According to Faysse (2006), the primary goal of a multi-stakeholder platform is to empower and actively engage stakeholders in seeking solutions to shared challenges. In this context, ICESP aims to identify gaps and peculiarities, and potential solutions for implementing the circular economy. Multi-stakeholder platforms are essential in fostering involvement and cooperation among various actors, facilitating the collective development of skills and knowledge. These platforms significantly enhance connectivity and incentivize collaboration among stakeholders, thereby facilitating the exchange of information and resources (Hedberg and Šipka, 2020). The interviewee noted:

"Organizations participating in ICESP contribute resources in terms of personnel who engage in activities, including WGs, as well as best practices in the circular economy, generating various outputs and operational responses to support the transition to a circular economy. It is the work of many minds".

Collaboration among diverse stakeholders enables the creation of synergies and accelerates the dissemination of best practices (Mangla et al., 2021). The outcomes of these collaborations are evident in the publication of research and position papers, as well as the realization of best practices.

Synergistic collaboration among these actors is essential for building an innovation ecosystem (Pushpanathan and Elmquist, 2022; Thomas et al., 2022). In this context, stakeholders foster sustainable innovation through cooperation and knowledge sharing, stimulation dynamic and intensive knowledge flows (Romano et al. 2014; Carayannis and Campbell 2009; de Vasconcelos Gomes et al., 2023). Several platform actors have contributed to the realization of innovations and best practices in the circular economy. Similarly, networks significantly enhance IC by acting as sources of valuable knowledge (Nonaka and Takeuchi, 2007; Jordão, 2015; Jordao and Novas, 2017). ICESP has developed a Good Practices review to raise awareness and promote a shared understanding of tangible perspectives on the circular economy. These good practices encompass relevant initiatives, innovative processes and 'learning from experience' examples involving companies or other key stakeholders such as research, academia and civil society (ICESP, 2018). In accordance with this vision, ICESP's good practices represent a source of knowledge. Related to this, the interviewee argued that:

"Currently, 245 good practices have been identified. The website features a section specifically dedicated to Circular Economy Best Practices, where these practices can be viewed. Practices are categorized into Consumption, Waste Management, Innovation and Investment, Secondary Raw Materials, and Production areas. Each practice is documented by filling out a form: the first section includes general information such as title, thematic scope, sector, geographical location, and any received funding; the second section details the practice itself, including achieved qualitative/quantitative results, potential replicability, challenges, and keywords. Finally, the third section includes contact details of the company and the form filler. Their dissemination across the national territory also promotes their spread and encourages the development of new initiatives based on existing examples, which are typical of our country's tradition".

Therefore, it is clear why, from ICESP's perspective, best practices become crucial sources of knowledge for achieving a circular economic model and key drivers for the transition to a sustainable economy. Due to their replicability, best practices allow for the achievement of goals with maximum efficiency and quality by referencing successful cases. These cases can serve as a primary reference for similar interventions, even in different contexts. On this point, the interviewee states:

"The goal of ICESP is to contribute to the emergence of a society oriented towards the circular economy and to support stakeholders in understanding the challenges and methodologies for implementing circular economy practices. Knowledge sharing and promotion also occur through organizing conferences. There is an annual conference where the results and works of the WGs are presented. Additionally, WGs organize conferences on specific topics. For example, a conference was held on the European directive on packaging

to provide insights into the implications of this regulation and discuss strategies for managing associated challenges. In this way, the output of the ICESP activities – such as the best practices – represent knowledge resource for all our members”.

It is evident that the role of ICESP participants is crucial in disseminating circular economy principles across their territories and networks, at all societal levels and throughout every stage of the value chain. The collection and sharing of the best practices can have a multiplier effect; the database serves as a valuable repository of circular economy solutions, accessible to the community to facilitate and accelerate the transition to a circular economy.

5.3. Digital platform supporting policymakers

Policymakers at a various level prioritize the protection of innovation processes as institutional support is essential for ensuring that investments in innovation activities achieve their intended effectiveness (Rosenbusch et al., 2019).

ICESP plays a pivotal role in supporting Italian policymakers by facilitating knowledge sharing, offering strategic consultancy, policy monitoring, promoting innovation, provide training, fostering international collaboration, and integrating policy.

The interviewee emphasized this aspect, arguing that:

“As stakeholders, we also engage with policymakers, as well as businesses. We have contributed to the national circular economy strategy. We participated in the consultation when the strategy was launched, and many of our comments were incorporated into the new version of the current strategy (...). Institutions sometimes approach us for clarification on specific issues and to gain an overview”.

ICESP has established a working group (WG 2) to facilitate dialogue between sector operators and policy makers regarding the latest policy tools, governance frameworks, and their potential developments. The group’s goal is to identify regulatory and economic instruments that can support the transition to a circular model. ICESP also conducts monitoring and evaluation activities on circular economy policies and initiatives, providing valuable feedback to policy makers. This feedback helps them the effectiveness of their policies and identify areas for potential adjustments. Additionally, ICESP offers technical and strategic consultancy, supplying policymakers with essential information to develop and implement effective policies, including scientific data, economic analyses, and evidence-based policy recommendations.

2.1.6 Conclusion and implications

ICESP is an initiative promoted by the Italian Ministry of the Environment, aimed at coordinating and advancing activities related to the circular economy among various public and private actors in Italy. It stands as an exemplary model of how stakeholders can collaborate to tackle environmental challenges and promote the circular economy. This study explores the contribution of collaborative platforms in the creation and dissemination of circularity best

GRINS – Growing Resilient, Inclusive and Sustainable

“9. Economic and financial sustainability of systems and territories”

Codice identificativo: PE00000018

practices. The findings show that the national-level stakeholder dialogue has enabled the identification and promotion of various strategic actions, encompassing different types of innovation. The platform represents a new paradigm of governance and collaboration, integrating the principles of the Quintuple Helix, Stakeholder Theory, and knowledge sharing. In line with the Quintuple Helix approach, ICESP fosters collaboration among governments, universities, industries, civil society, and the natural environment, recognizing that sustainable innovation necessitates the integration of multiple perspectives and expertise. Consistent with stakeholder theory, the platform underscores the importance of involving a broad aspect of stakeholders in the decision-making process, ensuring that policies reflect the needs and expectations of all actors involved. ICESP's ability to facilitate interaction among different actors and efficiently coordinate resources serves as a catalyst of growth and continuous innovation in the global economy. The platform's approach is not only significant for its theoretical contribution but also for its practical implications, particularly in promoting sustainable policies and business-oriented innovation. As a digital platform, ICESP acts as a catalyst for creating a network of stakeholders, fostering the development and exchange of best practices. This supports policymakers in defining and implementing the regulatory changes needed to accelerate the circular economy. Additionally, ICESP serves as a hub for sharing best practices, innovative solutions, and knowledge, enabling stakeholders to identify and collaboratively address operational challenges within the circular economy. The importance of an inclusive decision-making process is highlighted: by involving stakeholders, the platform ensures that policies and strategies are more effective and aligned with the real needs of the actors involved. ICESP stands as a pivotal driver in the sharing and effective utilization of knowledge, playing a key role in generating both tangible and intangible value. This value creation is fuelled by the synergistic interaction among actors, as highlighted by Chuang and Lin (2015), who emphasized the value of integrating various categories of stakeholders in such dynamics. ICESP emerges as a distinctive digital innovation ecosystem. The ability to generate value is not only a result of collaboration but is significantly enhanced by the digital platform, which facilitates knowledge sharing and networking, an aspect crucial in stakeholder community, as discussed by Dedehayir et al. (2018) and Senyo et al. (2019). ICESP has also secured essential institutional approval, which is vital for the sustainability of any innovation ecosystem. According to Romano et al. (2014), institutional endorsement provides a solid foundation for the development and growth of such ecosystems. Furthermore, the government's role in promoting the adoption of circular economy practices through platforms for design thinking and infrastructures development is crucial for fostering sustainable development (Patwa et al., 2021). In conclusion, ICESP represents an advanced model of collaboration and innovation that bridges theory and practice to advance the circular economy. Through its digital platform and active stakeholder involvement, it facilitates knowledge sharing and the implementation of best practices, making a significant contribution to sustainable development and continuous innovation.

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2.2 Enabling circularity through stakeholder engagement to digital transformation: lessons from the Italian textile industry

2.2.1 Introduction

While the textile industry plays a significant role in the global economy contributing to employment, trade, and economic growth, it also generates the most environmentally and socially negative consequences (Roy et al., 2020). Factors such as increased sales per capita, the turnover of fashion trends, and the decline in garment quality have adversely impacted environmental sustainability (Rahaman et al., 2024). Criticisms against the textile industry also include its excessive energy and water consumption, generation of massive waste, and exploitation of workers in developing countries (Abbate et al., 2023). In response to these social and environmental challenges, the circular economy (CE) offers a promising solution for more sustainable development in the textile industry. The CE advocates for a change of mindset that includes reducing, reusing, and recycling resources to minimise waste and maximise efficiency, offering a transformative paradigm for textile production and consumption (Ellen MacArthur Foundation, 2024). Embracing CE demands a radical transformation within firms as they need to rethink their business models from how products are conceived to how customers, and stakeholders in general, interact with them and participate in decision-making processes (Kwarteng et al., 2022). This shift demands innovative and creative solutions, with digital technologies (DTs) identified as catalysts for the transition toward CE business models and their success. Recent academic literature offers insights into the diverse applications of DTs that contribute to the effective implementation of CE strategies (Awan et al., 2021; Bhattacharjee et al., 2023). Technologies enable companies to optimise resource use, track material flows, and implement sustainable practices more effectively (Gupta et al., 2019; Nouinou et al., 2023). For example, blockchain can ensure supply chain transparency, addressing ethical concerns related to labour practices and material sourcing (Badhwar et al. 2023). Similarly, AI-driven virtual prototyping reduces material waste, while big data analytics facilitates predictive maintenance and process optimisation.

Despite the increasing number of studies on DTs in CE management, many still focus solely on exploring the technical and environmental aspects, overlooking the broader cultural and social dimensions of CE implementation (Awan et al., 2021; Chauhan et al., 2022; Gupta et al., 2019). Particularly, there is a gap in understanding the role of stakeholder engagement, collaboration, and value co-creation interlinked with DTs to enhance CE outcomes (Jia et al., 2020; Modgil et al., 2021). Some scholars agreed that stakeholder engagement (SE) plays a significant role within DTs (Moggi & Dameri, 2021; Kujala et al., 2023) by emphasising that only engaged stakeholders are eager and capable of understanding, using, and sharing the benefits of DTs for CE success, through optimised stakeholder interactions (Gandolfo & Lupi, 2021; Rajala et al., 2018; Kolade et al., 2022; Oberholzer & Sachs, 2023). Thus, how stakeholder interactions are framed and optimised through firm-stakeholder engagement practices to foster DTs within the CE paradigm is still an under-researched area, which merits further attention (Awan et al., 2021; Chauhan et al., 2022; Gupta et al., 2019).

This chapter aims to bridge this gap by investigating how stakeholder engagement acts as a catalyst for leveraging DTs within the CE of the textile industry. In this endeavour, employing the relational models where stakeholders operate (Bridoux & Stoelhorst, 2016) and the dimensions (Aksoy et al., 2022) and components (Oberholzer & Sachs, 2023) of stakeholder engagement as theoretical backgrounds, we adopt qualitative multiple case studies focusing on 17 firms' part of a luxury fashion engineering conglomerate based in Italy. These multiple cases studies approach allows for an in-depth exploration of complex phenomena within a well-defined context (Eisenhardt & Graebner, 2007; Yin, 2014). The selected cases provide a rich context for examining how stakeholder interactions and digital innovation converge to foster circularity.

Our findings contribute to the growing body of literature on CE by highlighting the critical role of stakeholder engagement in enabling digital transformation for sustainability. By exploring the social dimensions of CE implementation, we provide insights into how relational dynamics and value co-creation can amplify the impact of DTs. Furthermore, we propose a replicable framework for integrating stakeholder engagement and digital innovation, offering practical guidance for managers and policymakers seeking to transition toward circular business models.

2.2.2 Theoretical background

Environmental and Social Challenges in the Textile Industry

The textile industry plays a crucial role in the global economy, valued at approximately USD 1.3 trillion and employing over 300 million people across the entire production chain (Ellen MacArthur Foundation, 2024). From 2000 to 2022, worldwide textile fibre production grew from 58 to 116 million tonnes, with projections indicating it will reach 147 million tonnes by 2030 (Textile Exchange, 2023).

However, despite its economic significance, the textile sector's expanding demand for clothing, combined with a 36% reduction in the average lifespan of garments, leads to significant environmental and social challenges. The overproduction and rapid turnover of clothing result in millions of tonnes of textile waste each year, much of which ends up in landfills, is incinerated or is exported, while only a small fraction is recycled (Bosch Meier et al., 2024).

Textile production also contributes to water pollution through the release of harmful chemicals and microfibres, along with an increase in greenhouse gas emissions. In 2020, the textile industry, from raw material production to waste management, was responsible for generating 121 million tonnes of CO₂, making it one of the leading sectors in terms of climate change impact (European Environment Agency, 2023). Beyond environmental concerns, the textile industry also poses significant social issues. Unrealistic production targets and the promotion of low-wage contracts negatively affect workers, many of whom endure poor working conditions with daily wages often far below the poverty threshold (Annapoorani, 2017). Scholars highlight that technology plays a crucial role in advancing the CE, addressing implementation challenges and unlocking opportunities for more sustainable practices (Awan et al., 2021; Bhattacharjee et al., 2023).

Digital technologies to foster CE

The role of technology in advancing the CE) cannot be overstated, as it provides the tools and systems necessary to address complex sustainability challenges and enhance resource efficiency. By enabling traceability, optimizing resource use, and redesigning products for circularity, technology serves as a cornerstone for driving the transition to a CE. For instance, blockchain technology is a transformative tool that ensures transparent and traceable supply chains. It addresses critical issues such as unethical labour practices, human resource exploitation, and opaque sourcing of raw materials. By recording data that is unchanging on the origin of materials, blockchain

infers confidence in ethical sourcing and compliance with sustainability standards (Badhwar et al., 2023).

Moreover, big data analytics offers textile manufacturers unprecedented insights into their operations. Through predictive maintenance and real-time monitoring of production processes, manufacturers can preempt equipment failures, reduce downtime, and optimize resource consumption. These capabilities significantly minimize material waste and energy use, thus enhancing the overall efficiency of production systems (Nouinou et al., 2023).

Additionally, artificial intelligence (AI) and machine learning algorithms play a pivotal role in promoting CE principles. These technologies analyze vast datasets to identify patterns and opportunities for redesigning products and processes. By embedding CE principles such as modularity and recyclability into product design, AI enables the creation of items that are easier to repair, upgrade, or recycle. This fosters a shift from traditional linear production models to sustainable, circular design approaches (Gupta et al., 2019). However, leveraging these technological advancements requires more than just innovation; it demands organizational change and proactive stakeholder engagement. Companies must foster collaboration among diverse stakeholders, including suppliers, consumers, and regulators, to ensure that technological solutions align with broader CE goals. Such alignment facilitates the integration of technologies into existing processes, making circular practices both practical and scalable (Bocken et al., 2022).

Stakeholder engagement

The stakeholder approach offers a comprehensive framework for understanding how companies can effectively integrate CE principles into their business strategies through collaboration (Kujala et al., 2023). This perspective highlights the necessity of engaging with all relevant stakeholders to develop innovative and sustainable solutions for CE challenges (Gupta et al., 2019). First, Bridoux and Stoelhorst (2016) identify three relational models that enhance stakeholder contributions to joint value creation, moving beyond traditional market-based frameworks where individuals act primarily in their self-interest. Communal sharing prioritizes consensus, community, and collective identity, fostering a shared sense of purpose through collective decision-making. Authority ranking leverages hierarchical structures, where a superior entity coordinates and directs actions, with subordinates adhering to the guidance provided. Equality matching emphasizes balanced reciprocity and

equitable relationships among stakeholders, ensuring mutual benefit and fairness in their interactions (Fiske, 1991).

Expanding on these models, Aksoy et al. (2022) outline three key strategies for fostering stakeholder engagement. Stakeholder recognition involves identifying all relevant stakeholders and understanding their interests, concerns, and potential impact on the organization. Stakeholder support entails providing stakeholders with social benefits, such as investments in education, initiatives promoting diversity, and other community-focused programs. Stakeholder dialogue emphasizes continuous, meaningful exchanges of information that extend beyond transactional relationships to include ongoing interaction with multiple stakeholders simultaneously.

Finally, Oberholzer and Sachs (2023), along with Kujala et al. (2023), further classify stakeholder engagement into three approaches: moral, pragmatic, and strategic. The moral approach underscores the ethical obligations of organizations toward all stakeholders, including those with indirect impacts, by fostering trust, legitimacy, transparency, and minimizing harm to both stakeholders and the environment. The pragmatic approach focuses on achieving practical benefits for the organization by fostering collaborative problem-solving and building long-term partnerships that align with shared goals. The strategic approach aims to gain a competitive edge by leveraging stakeholder relationships to drive innovation and organizational success. Synthesizing these perspectives, this study adopts the theoretical framework presented in Figure 1 to investigate how firm-stakeholder engagement practices are framed and how these interactions facilitate the integration of DTs to advance CE initiatives.

Figure 1 – Theoretical framework

THEORETICAL FRAMEWORK			OUTPUTS	
RELATION MODELS	STAKEHOLDER ENGAGEMENT	STAKEHOLDER ENGAGEMENT COMPONENTS	DTS	CE (Implications and impacts)
<i>Bridoux and Stoelhorst (2016)</i>	<i>Aksoy et al. (2022)</i>	<i>Oberholzer and Sachs (2023)</i>	Blockchain IoT AI Machine Learning ...	
<i>Four distinct approaches to enhance stakeholders' contributions to joint value creation.</i>	<i>Stakeholders develop their interactions, relationships, and collaborations by delineating three key strategies:</i>	<i>Stakeholder engagement can be classified into three distinct approaches:</i>		
	- Recognition - Support - Dialogue	- Moral - Strategic - Pragmatic	STAKEHOLDER INVOLVED Suppliers Employees Managers Governments Academia NGO Entrepreneur Consumers Incubators ...	

2.2.3 Methodology

This study employed a qualitative research methodology, focusing on multiple case studies to investigate a specific phenomenon (Eisenhardt & Graebner, 2007; Siggelkow, 2007; Yin, 2014). The multiple case studies approach is particularly effective for examining complex situations within a well-defined context (Stake, 1995; Eisenhardt et al., 2016) and is especially suited to addressing "how" and "why" questions (Yin, 2014). The research was conducted in three phases (Stake, 1995).

In the exploratory phase, secondary sources such as scientific journals, newspapers, magazines, databases, and websites were reviewed to gain insights into the CE in the textile industry, with a focus on challenges, best practices, and stakeholder engagement in digital transformation for CE. The second phase focused on the identification of target companies, culminating in the selection of 17 luxury brand companies as part of a luxury fashion engineering conglomerate based in Italy chosen by financial success (evidenced by revenue growth in 2023), and comprehensive value chain coverage. The second phase involved primary data collection. The research team visited the companies' headquarters and conducted interviews with the CEOs, managers and AI technicians. A semi-structured interview protocol, informed by stakeholder engagement literature, was used to gather insights into the role of stakeholder engagement in driving digital transformation (DT) within the circular economy (CE) in the textile industry.

The interviews were recorded, transcribed, and independently analyzed by researchers to minimize subjectivity. The findings were cross compared to ensure consistency and accuracy.

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In the supplementary data and analysis phase, additional information was collected from the companies' financial statements, official website, and reputable business platforms, including Sole 24 Ore, Financial Times, Pambianco News, and Fashionnetwork. Data triangulation (Eisenhardt, 2016; Yin, 2003) was employed to enhance the reliability of the findings. A theoretical framework (Figure 1) was then used to analyze how stakeholder engagement acts as a catalyst for DT within the CE in the textile industry.

2.2.4 Findings

In this section, we present the findings derived from the research protocol detailed in the methodology. The focus is on the pivotal role of stakeholder collaboration in advancing CE practices through the integration of innovative technological solutions. Specifically, this discussion explores three critical processes integral to the adoption of CE: prototyping, supply chain management, and production. Each process is examined to highlight the relational approaches, key dimensions, and components of stakeholder engagement that enable and sustain the transition to CE practices.

Stakeholder Collaboration to Develop AI-Based Virtual Prototyping to Address Customer Needs

The prototyping phase represents the initial stage where the conglomerate harnesses technology and stakeholder input to establish the foundation for circular economy (CE) practices. During this stage, two distinct relational models come into play. First, under the market pricing relational model, the companies identify and respond to the needs of their clients, particularly luxury brands. The companies aim to maintain or enhance sales by aligning the strategy with client demands, and strategically positioning itself within the market. This alignment catalyzed the adoption of AI, a key enabler for virtual prototyping.

The development of AI was facilitated by activating a second relational model, equality matching, which fosters collaboration with external stakeholders, including research institutions, technology startups, and academia. These partnerships create a platform for dialogue, enabling the co-development of tailored solutions to address specific CE challenges.

AI-driven virtual prototyping directly supports the CE principles of virtualization and reduction, significantly mitigating carbon emissions. Traditionally, the creation of physical prototypes involved substantial material consumption and generated high levels of carbon emissions due to transportation and resource wastage. Virtual

prototyping, powered by AI, revolutionizes this process by eliminating the need for physical samples, enabling rapid design iterations with minimal environmental impact.

This innovative approach not only reduces material usage but also dramatically lowers the carbon footprint associated with design activities.

Stakeholder Pressure to Promote Knowledge Sharing and Transparency in the Supply Chain via Blockchain

The supply chain phase builds on the principles established during prototyping, emphasizing transparency and efficiency. Stakeholder engagement becomes more intricate, with two relational models driving collaboration.

Through equality matching, companies foster knowledge sharing between their members and suppliers. This exchange ensures that all parties are aligned on sustainability goals, with transparency as a key objective. Concurrently, authority ranking highlights the role of external pressures, such as government regulations, in encouraging the adoption of CE principles. Regulatory frameworks provide pragmatic support, compelling the organization to align its operations with environmental and social standards.

Blockchain technology plays a pivotal role in this phase by enabling traceability throughout the supply chain. Blockchain ensures that every stage of the product life cycle is mapped, providing a transparent view of material flows and identifying inefficiencies. This technology also allows companies to optimize supplier selection, prioritizing those located closer to production hubs to reduce transportation-related emissions. Moreover, blockchain facilitates the sharing of information through QR codes, ensuring that all stakeholders—internal and external—can verify the traceability and sustainability of materials.

The CE principle of reduction is exemplified here, as blockchain helps minimize the environmental impact of supply chain operations. By selecting geographically closer suppliers and improving resource efficiency, the organization reduces its overall carbon emissions while fostering trust and accountability among stakeholders.

Collaboration, Training, and Commitment Driving Waste-Reducing Production Technologies

The final phase, production, is where companies fully integrate circular practices into their operations. Stakeholder engagement intensifies, with a focus on collaboration, training, and moral commitment to sustainability.

Under the authority ranking model, companies assume a leadership role in educating their workforce. Training programs and educational initiatives equip employees with the skills needed to implement advanced CE technologies effectively. Meanwhile, communal sharing emphasizes the moral responsibility of all stakeholders to work collectively toward creating circular value. This shared sense of purpose ensures that CE principles are upheld across the board. Operating as a decentralized network of formerly independent small and medium-sized enterprises (SMEs), the organization has unified these entities under a shared commitment to leveraging DTs and advancing CE practices. Each company within the conglomerate retains its original management and specializes in unique crafts, such as leatherwork and knitwear, thereby preserving regional craftsmanship while fostering a culture of innovation and sustainability.

The above-mentioned relational models lead to the development of DTs that boost the CE implementations. The CE principles of reduction and recycling are most prominent in this phase. Digital printing technology reduces fabric waste by enabling precise ink application and cutting material wastage by 40%. Additionally, additive manufacturing, such as 3D printing, enhances resource efficiency by producing components with minimal waste. Finally, upcycling and recycling processes transform discarded fabrics into valuable materials like cashmere, wool, or even car upholstery. These innovations demonstrate how technology can turn waste into new opportunities, closing the loop in the production cycle.

By minimizing fabric waste and repurposing discarded materials, the conglomerate ensures that resources are used as efficiently as possible, aligning production processes with the broader goals of circularity and sustainability.

Figure 2 – Findings

	RELATION MODELS	STAKEHOLDER ENGAGEMENT	STAKEHOLDER ENGAGEMENT COMPONENTS	TECHNOLOGY	CE PRINCIPLE
Prototyping	Market pricing The conglomerate recognized the need of clients (luxury brands)	Recognition	Strategic: increasing sales	ARTIFICIAL INTELLIGENCE	Virtualize - the prototype eliminates the need for physical prototypes Reduce - carbon footprint
	Equality Matching Conglomerate collaborate with other companies, research institutions, Academia or technology startups to advance CE.	Dialogue	Strategic: advance technological innovations for CE.		
Supply chain	Equality Matching Knowledge and data exchange among conglomerate members and suppliers.	Dialogue	Strategic: transparency in the supply chain)	BLOCKCHAIN	Reduce - prompting the company to optimize by selecting suppliers closer in proximity
	Authority ranking The government puts pressures on the CE principle embracement	Support	Pragmatic: rules and regulations		
		Recognition			
Production	Authority ranking The leader acquires and trains all new members of the conglomerate	Support through training and educational courses.	Strategic: improve CE performance	DIGITAL PRINTING ADDITIVE MANUFACTURING	Recycle - new life for discarded fabrics as cashmere, wool, or even car upholstery materials
	Communal sharing All stakeholders need to work from moral standing to create circular value	Dialogue	Moral		
	Market pricing Conglomerate sells scarps to external companies specialized in waste.	Support	Strategic: minimizing waste	UPCYCLING/RECYCLING	Reduce - fabric waste

2.2.5 Theoretical contributions

This study makes theoretical contributions to advancing academic understanding in the fields of stakeholder engagement, digital transformation, and the CE.

First, the research drawing on stakeholder approach literature applies the relational models—communal sharing, equality matching, and authority ranking—within the context of CE practices. This theoretical contribution enriches the existing literature by linking these relational models explicitly with the dynamics of DTs and CE principles, a domain that has still been underexplored. Bridoux and Stoelhorst's (2016) relational frameworks are instrumental in illustrating how varying stakeholder engagement strategies can foster collaboration and joint value creation, thereby amplifying the impact of digital solutions on sustainability outcomes.

Second, the study broadens the scope of CE literature by addressing the often overlooked social and relational dimensions of CE implementation. While prior research has primarily concentrated on environmental and technical considerations, this work highlights the essential role of stakeholder dynamics in fostering value co-creation in the CE ecosystem. By incorporating frameworks from Aksoy et al. (2022) and Oberholzer and Sachs (2023), the research demonstrates how stakeholder engagement, collaboration, and dialogue catalyze the adoption and scaling of CE practices. These theoretical advancements provide a more holistic understanding of

CE by bridging the gap between technology-driven solutions and their social underpinnings.

Moreover, by emphasizing tools such as artificial intelligence (AI), blockchain, and additive manufacturing, the research elucidates the interplay between technological advancements and stakeholder interactions. These synergies underscore the transformative potential of DTs when coupled with inclusive and well-structured engagement strategies. For example, the study reveals how AI-driven virtual prototyping can reduce material waste and carbon emissions by enabling iterative design processes without relying on physical samples, aligning with Gupta et al. (2019) and Nouinou et al. (2023). Similarly, blockchain technology enhances transparency and traceability in the supply chain, addressing ethical concerns and fostering trust among stakeholders, as highlighted by Badhwar et al. (2023).

2.2.6 Managerial contributions

From a managerial standpoint, this study offers significant insights for leaders operating within CE networks, particularly in the textile industry. This sector, which often relies on small and medium-sized enterprises, can benefit greatly from adopting a networked perspective to successfully navigate the transition to CE (Abbate et al., 2023). To facilitate this shift, the study proposes a replicable "rulebook" of stakeholder engagement practices that can enhance the impact of DTs on CE initiatives. This framework empowers industry players to adopt an ecosystemic perspective in their journey toward sustainable and circular business practices.

Managers are encouraged to prioritize stakeholder engagement as a cornerstone of their CE strategies. Collaborative models, such as communal sharing and equality matching, are emphasized as effective approaches to drive innovation and sustainability. Establishing meaningful dialogue among diverse stakeholders, including suppliers, regulators, and employees, is crucial for aligning organizational activities with CE objectives. For example, blockchain technology emerges as a pivotal tool for achieving supply chain transparency. By enabling traceability throughout the product lifecycle, blockchain fosters accountability and supports ethical material sourcing, addressing both regulatory demands and consumer expectations for sustainability (Gandolfo and Lupi, 2021).

Organizational change is another essential area of focus for managers. The research underscores the importance of investing in training and capacity-building programs to equip employees with the skills required to implement CE-driven digital solutions.

The multiple case studies demonstrate how leadership's emphasis on educational initiatives fosters a cultural shift toward sustainability, aligning organizational goals with broader societal and environmental imperatives (Oberholzer and Sachs, 2023). Strategic supplier partnerships further enhance the implementation of CE practices. By prioritizing suppliers based on geographic proximity and sustainability standards, companies can reduce transportation-related emissions and strengthen supply chain resilience. Blockchain technology plays a crucial role in optimizing supplier selection, ensuring alignment with CE objectives and fostering collaboration among all supply chain stakeholders.

Finally, collaboration with policymakers is essential for designing and complying with sustainability regulations. Such partnerships not only ensure regulatory compliance but also create opportunities for long-term strategic benefits. By aligning organizational practices with policy frameworks, managers can achieve a competitive advantage while contributing to the broader adoption of circular business models. These insights collectively offer a comprehensive roadmap for leveraging stakeholder-driven digital innovations to promote sustainability in the textile industry and beyond, addressing challenges across diverse sectors.

2.2.7 Limitations and future research agenda

This study provides significant insights into the integration of SE and DTs within CE practices. However, it has some limitations. First, the multiple case study approach, focusing on luxury Italian textile companies, restricts the generalizability of the findings to broader contexts (Eisenhardt & Graebner, 2007; Yin, 2014). While the study offers practical insights into CE implementation, its applicability to other industries, regions, or organizational scales—each with unique stakeholder dynamics and technological capacities—remains uncertain. To address this, future research should include comparative studies across different sectors, geographic regions, and organizational sizes to explore how SE strategies and DT applications vary in diverse contexts (Bridoux & Stoelhorst, 2016).

Second, adopting interdisciplinary approaches that incorporate insights from behavioural science, cultural studies, and economics could provide a deeper understanding of SE and value co-creation in the CE ecosystem (Aksoy et al., 2022). These perspectives could illuminate the social and cultural dynamics that shape stakeholder interactions and enhance the impact of DTs.

Third, the development of comprehensive metrics and frameworks to assess the effectiveness of stakeholder-driven DTs in achieving CE objectives would offer practical tools for managers and policymakers. Such tools would enable organizations to measure progress, identify gaps, and refine their strategies for integrating digital innovations into circular business models.

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2.3 Cognitive Biases in the Circular Economy: Implications for Stakeholder Engagement and Decision-Making

2.3.1 Introduction

The current linear economic paradigm, often characterised by the "take-make-dispose" model, has exacerbated the challenges of resource depletion and escalating waste generation (Preston, 2012). The circular economy (CE) has emerged as a transformative framework for resource regeneration and restoration (Ghisellini et al., 2016). The CE model emphasizes reducing resource consumption, reusing materials, and recycling products to enhance resource efficiency and minimize waste (Ellen MacArthur Foundation, 2024). As a holistic approach, the CE necessitates a systemic transition that extends beyond organizational boundaries, requiring collaboration among interconnected stakeholders to achieve shared economic, social, and environmental objectives (Aarikka-Stenroos et al., 2023).

Despite the growing interest in CE among scholars and practitioners, the majority of research has concentrated on its ecological dimensions, often neglecting the critical social dynamics that underpin stakeholder engagement. Specifically, limited attention has been paid to the role of stakeholders' perceptions, values, and behaviours in shaping CE outcomes (Beaurain et al., 2023; Murray et al., 2017; Korhonen et al., 2018; Souza Piao et al., 2024). This narrow perspective fails to address the influence of cognitive biases—systematic deviations from rational judgment—that act as barriers to stakeholder decision-making in CE initiatives (Cristofaro et al., 2023).

A significant challenge in advancing CE lies in overcoming human cognitive limitations, which are often rooted in heuristics and biases (Tversky & Kahneman, 1974). While these mental shortcuts facilitate decision-making under uncertainty, they frequently lead to systematic mistakes that weaken sustainability goals. Cognitive biases influence stakeholder attitudes and decisions, creating resistance to change and impeding the adoption of circular practices. Addressing these biases is therefore critical for fostering the collaborative and systemic changes required for a successful transition to a circular economy.

Drawing upon the established literature on cognitive biases in sustainability-related decision-making (Palmucci & Ferraris, 2023) and adapting these concepts to the CE context, this paper aims to deepen our understanding of CE. It explores the impact of cognitive biases on CE by examining how they influence the engagement of internal and external stakeholders in CE initiatives.

To achieve this, a qualitative methodology was employed, including interviews with NGOs, suppliers, and consumers to gain a richer understanding of stakeholder dynamics. The collected data was analyzed using the Gioia method (Gioia et al., 2013), enabling the identification of recurring themes and theoretical insights.

By focusing on the interplay between cognitive biases and the circular economy, this research contributes to a deeper understanding of CE transitions' behavioural and psychological dimensions. From a theoretical perspective, results provide a novel lens on CE adoption by identifying cognitive biases such as status quo bias, temporal discounting, and framing effects as critical barriers to stakeholder collaboration.

The findings also provide practical insights for managers and policymakers in CE transitions, highlighting the importance of addressing cognitive biases to effectively enhance stakeholder engagement and support the adoption of circular practices.

2.3.2 Literature Review

Circular Economy and Stakeholder Theory

The CE rooted in the principles of resource optimization, extending product life cycles, and minimizing waste, represents a regenerative system aimed at maximizing resource utility for as long as possible (Ellen MacArthur Foundation, 2024). Embracing CE necessitates a profound transformation within organizations, requiring companies to rethink their business models—not only in terms of product design but also in how stakeholders are involved in decision-making processes (Kwarteng et al., 2022). Thus, in addition to technical advancements—such as innovative technologies for optimizing resource use, monitoring material flows, and improving the implementation of more ecological practices—stakeholder involvement plays a crucial role in enabling the transition to a circular business model (Aarikka-Stenroos et al., 2023; Fobbe & Hilletoft, 2023). Drawing on stakeholder theory, several scholars argue that effective stakeholder engagement and collaborations emerge as necessary conditions for implementing CE (Geissdoerfer et al., 2017; Gupta et al., 2019; Shultz et al., 2024). For example, Moggi and Dameri (2021) argue that stakeholder engagement significantly shapes directions, effectiveness, and overall impact of CE initiatives. Similarly, Brown and Bajada (2018) assert that engaged stakeholders enhance resource circularity within networks, creating greater sustainable value. Additionally, Mishra et al. (2019) demonstrate that involving multiple stakeholders strengthens supply chain circularity, particularly in the context of developing countries. However, transitioning from linear to circular systems is not without challenges. Stakeholder alignment is critical, as creating shared values and fostering CE-positive attitudes require trust and collaboration within stakeholder networks to effectively address CE challenges (Oberholzer & Sachs, 2023). For example, Meath et al. (2022) demonstrate that in multi-level collaboration for the transition to the CE) the shared vision was crucial for aligning and coordinating the various actors involved—industry, academia, and government—and for overcoming known barriers, leveraging enabling factors, and addressing key success factors. Similarly Gupta et al. (2022) highlight that a unified vision and shared sustainability goals within a CE system foster mutual support, strengthen relational ties, and enable effective use of shared resources. The CE transition also demands a holistic and inclusive approach that transcends traditional industrial and sectoral boundaries, reconciling diverse and often conflicting

stakeholder priorities (Castro-Lopez et al., 2023; Shultz et al., 2024). For instance, businesses often prioritize economic profitability, NGOs advocate for environmental benefits, and consumers seek accessible and affordable solutions. Aligning these competing interests is essential but frequently fraught with tension (Salminen et al., 2023). While businesses may view CE-related changes as disruptive or costly, policymakers often focus on short-term regulatory compliance rather than long-term sustainability goals. These challenges to stakeholder engagement are further compounded by cognitive biases, which distort perceptions of risks, benefits, and responsibilities (Cristofaro et al., 2023). Cognitive biases can limit stakeholder engagement by impairing decision-making processes, misaligning organisational actions with stakeholder needs, and hindering effective dialogue and collaboration (Rinaldi, 2020). Addressing these biases is critical to fostering meaningful stakeholder engagement and advancing collaboration for successful CE initiatives.

Cognitive biases related to environmental sustainability choices

The concept of cognitive biases gained prominence in the 1970s, thanks to the pioneering work of Daniel Kahneman and Amos Tversky. Their research, known as the “Heuristics and Bias Program,” sought to understand how individuals make decisions in uncertain, ambiguous, or resource scarcity (Tversky & Kahneman, 1974). This groundbreaking research revealed that human decision-making does not follow purely rational processes but is often guided by heuristics, or mental shortcuts, simplifying complex decisions (Haselton & Buss, 2000; Kahneman & Tversky, 1979). Over time, cognitive biases have been recognised as systematic deviations from rationality, leading to errors in judgment (Kahneman & Tversky, 1981). Cognitive biases have become a central topic in behavioural science, with extensive research highlighting their implications across various fields. Environmental sustainability decisions, characterised by uncertainty and complexity, are especially prone to biases, making this a relevant study area (Hoffman & Bazerman, 2007). Unsustainable behaviours often stem from structural barriers, such as inadequate infrastructure, limited financial resources, or geographical challenges. For example, individuals living in rural areas may lack access to public transportation, making car dependency inevitable. Similarly, low-income

households may find it difficult to invest in expensive renewable energy technologies, such as solar panels (Gifford, 2011). However, beyond these structural constraints lies another critical factor: the psychological barriers shaped by cognitive biases. These biases influence how individuals perceive environmental issues and their willingness to adopt sustainable behaviours. Kahneman and Tversky's foundational work provides a lens to analyse these biases in the context of modern sustainability challenges. Availability Bias, for instance, is the tendency to judge the likelihood of events based on their accessibility in memory (Singh & Ryvola, 2018). For example, individuals who have not directly experienced severe climate events—such as floods, droughts, or hurricanes—may underestimate their likelihood, leading to a lack of urgency in adopting sustainable behaviours (Arvai et al., 2012). This bias explains why many decision-makers are not motivated to invest in environmental protection (Newell & Pitman, 2010). Another critical bias is the Framing Effect, described by Kahneman and Tversky in their 1981 study, "The Framing of Decisions and the Psychology of Choice." This bias highlights how the context or way a decision is presented can significantly influence choices. For instance, terms like "climate change" may fail to convey the gravity of the issue compared to stronger phrases like "environmental catastrophe." Similarly, images of global warming's consequences often lack the emotional impact needed to inspire action (Mazutis & Eckardt, 2017). Anchoring Effect Bias, closely related to framing, occurs when individuals rely too heavily on initial reference points in their decision-making. In sustainability, people may underestimate the impact of a 2–5°C increase in global temperatures because they compare it to natural seasonal variations, assuming the consequences are manageable (Mazutis & Eckardt, 2017). This perception reduces the sense of urgency needed to drive meaningful action (Newell & Pitman, 2010). Beyond these biases, Present & Discounting the Future Bias is a significant obstacle to environmental sustainability. This bias refers to the human tendency to prioritise immediate benefits over long-term gains, often leading to the dismissal of climate investments whose returns may only be realised decades later (Weber, 2017). Businesses, for instance, may under-prioritise pro-environment initiatives because they yield uncertain returns compared to traditional investments with higher short-term profits (Palmucci & Ferraris, 2023). Optimism Bias further complicates sustainability efforts. It

reflects the belief that future technological advancements will inevitably solve environmental challenges, delaying immediate action. This bias also leads people to assume that severe climate impacts will primarily occur in distant regions or far in the future, diminishing their perceived relevance (Shu & Bazerman, 2010). Additionally, egocentric biases like Diffusion of Responsibility and Anthropocentrism hinder collective action. Diffusion of Responsibility occurs when developed nations blame developing countries for climate inaction while developing countries attribute climate change to the historical industrialisation of the West. This mutual blame often results in a lack of coordinated efforts to address the issue (Mazutis & Eckardt, 2017). Anthropocentrism Bias reflects humanity's tendency to prioritise human needs over ecological concerns, framing sustainability as a way to secure the well-being of future generations while neglecting the broader ecosystem (Naudè, 2017). Single-action bias, another common obstacle, involves overestimating the impact of isolated environmental actions, such as recycling while ignoring other behaviours that contribute significantly to environmental degradation (Threadgold et al., 2022). This misplaced confidence can lead to complacency, as individuals believe their minimal efforts are sufficient. Finally, Confirmation Bias exacerbates resistance to change by causing individuals to favour information that aligns with their existing beliefs while rejecting contradictory evidence. This bias undermines the effectiveness of climate awareness campaigns, as sceptics often dismiss information that challenges their views (Newell & Pitman, 2010). These cognitive biases create significant psychological barriers to sustainability, influencing how individuals and organisations perceive and respond to environmental challenges. Addressing these biases requires targeted interventions, such as reframing environmental messages to evoke urgency, fostering collective responsibility, and designing policies that account for the complexities of human behaviour. Understanding and mitigating these biases can create more effective strategies for promoting environmental sustainability and driving meaningful action.

2.3.3 Methodology

This study employs a qualitative research design, using interviews and focus groups to gather insights from multiple stakeholders in the textile industry. The textile sector is a focal point because it plays a crucial role in exploring circular economy (CE) transitions and cognitive biases. Its ongoing efforts to shift from a linear "take-make-dispose" model to a regenerative circular system provide compelling examples that align closely with the objectives of our research (Saha et al., 2024).

Data collection focuses on managers of circular business models and participants in CE projects, including NGOs, suppliers, and consumers. This approach ensures a comprehensive understanding of the cognitive barriers faced by different stakeholders.

The Gioia method guides data analysis, identifying first-order themes and aggregate dimensions (Gioia et al., 2013). Questions are framed to uncover biases affecting CE engagement, drawing on established frameworks of cognitive biases in environmental decision-making (Palmucci & Ferraris, 2023). Data analysis involves coding responses to identify patterns and themes. First-order concepts capture specific instances of biases, such as reluctance to adopt new technologies or reliance on traditional business models. These concepts are then aggregated into higher-order dimensions, such as resistance to innovation or misaligned priorities. By systematically analyzing these dimensions, the study aims to develop a comprehensive understanding of how cognitive biases influence decision-making when implementing a circular economy.

2.3.4 Results

This study investigates the impact of cognitive biases on stakeholder engagement and decision-making within the CE. The prevalence of cognitive biases such as status quo bias, temporal discounting, single-action bias and availability bias emerged as significant barriers to effective CE adoption. Status quo bias, evident in the reluctance of businesses to alter established workflows, underscores the resistance to change ingrained in current practices. In the textile sector, for instance, companies expressed concerns about the operational disruptions and financial risks associated with shifting

to circular models. There is a preference for enhancing existing systems over radically rethinking processes, as seen in the statement about maximising current resource use *"We already do the maximum possible on sustainability"*. This reflects resistance to systemic innovation that could fundamentally reshape how circularity is implemented in the textile sector.

Consumers also demonstrated a preference for traditional purchasing habits, often choosing familiar products over sustainable alternatives despite their awareness of environmental benefits.

Temporal discounting biases further complicate the issue, with stakeholders frequently prioritizing short-term economic gains over the long-term benefits of sustainability. This tendency was evident in both consumer behavior, where cost considerations outweighed ecological concerns, and in business practices, where quarterly financial targets eclipsed investments in circular strategies.

For example, the CEO of a textile company emphasises short-term operational efficiency and sustainability, suggesting a potential undervaluation of long-term sustainability planning. This bias appears in discussions about reducing fabric waste and streamlining prototyping processes to save resources but with limited discourse on broader long-term environmental impacts.

The single-action bias also presents a challenge, where stakeholders disproportionately focus on isolated actions, such as digitalizing one aspect of production or reducing waste in a single process, while neglecting the need for systemic integration of circular economy principles across design and production. This approach risks creating a false sense of accomplishment, ultimately hindering the comprehensive transformation required for sustainability.

Lastly, availability bias, as demonstrated in the CEO's reference to the impact of COVID-19 on virtual prototyping, underscores how external shocks often drive change. The adoption of virtual prototyping became a necessity when physical prototyping was no longer feasible, illustrating how stakeholders are more likely to engage with CE initiatives after experiencing or witnessing significant negative events. This reactive approach to sustainability delays

proactive transitions and highlights the need for a more strategic commitment to circular economy practices.

Table 1 – Stakeholders' Biases in CE

Cognitive Bias	Description	Impact on CE Adoption
Status Quo Bias	Resistance to change, preference for maintaining current practices.	Hinders adoption of new circular models due to perceived risks.
Bias Present and Discount the Future	Prioritisation of short-term economic benefits over long-term sustainability goals.	Discourages investment in long-term sustainability solutions.
Single-Action Bias	Stakeholders often overestimate the impact of small individual actions, like recycling or purchasing an electric car, and use these efforts to ease their conscience, neglecting further contributions they could make toward broader circular economy initiatives.	This mindset limits the holistic transformation required for circular and may create a false sense of accomplishment.
Availability bias	The company believes that the stakeholders collaborate on circular economy initiatives when they have experienced or witnessed negative environmental and/or social events in the past.	This bias can result in reactive rather than proactive adoption of circular measures, delaying necessary transitions.

2.3.5 Discussion

The persistence of cognitive biases poses significant challenges to stakeholder engagement and decision-making within the circular economy (CE). These biases, including status quo bias, temporal discounting, single-

action bias, and availability bias, create psychological barriers that hinder the adoption of sustainable practices and the transition to a circular model.

Status quo bias often manifests as resistance to change, particularly in sectors like textiles, where stakeholders perceive CE adoption as risky or disruptive to established workflows. This bias underscores a preference for incremental improvements over systemic innovation. For example, companies frequently express satisfaction with existing sustainability measures, stating, "We already do the maximum possible on sustainability." This reluctance to embrace transformative change is consistent with findings that such bias inhibits progress by reinforcing existing practices and creating inertia (Cristofaro et al., 2023; Ghisellini et al., 2016). Addressing this bias requires showcasing successful transitions and offering financial incentives for early adopters, which can reduce uncertainty and build confidence in CE practices (Beaurain et al., 2023).

Temporal discounting complicates long-term planning by prioritizing immediate economic gains over enduring sustainability benefits. This bias is evident in business decisions that emphasize short-term cost efficiency, such as minimizing fabric waste, while undervaluing broader environmental impacts. As Palmucci and Ferraris (2023) suggest, educational initiatives and economic incentives can mitigate temporal discounting by emphasizing the lasting advantages of CE adoption, including cost efficiency and enhanced resource sustainability. Positive framing that highlights CE as an opportunity for value creation rather than an obligation is crucial for realigning stakeholder priorities.

Single-action bias further limits CE progress by creating a false sense of accomplishment among stakeholders who overestimate the impact of isolated actions. For instance, digitalizing one production process or improving waste management in a single area is often perceived as sufficient, neglecting the need for systemic integration of CE principles across design and production. This misplaced confidence risks complacency and undermines the holistic transformation required for sustainability (Threadgold et al., 2022). Overcoming this bias involves fostering a broader understanding of CE as a comprehensive, interconnected approach that requires sustained and collective effort (Fobbe & Hilletoft, 2023).

Availability bias illustrates how external shocks, such as the COVID-19 pandemic, can catalyze reactive changes in stakeholder behaviour. For example, virtual prototyping gained traction only after physical prototyping became infeasible, reflecting a reliance on immediate pressures rather than proactive planning. While such shocks can drive innovation, they often result in delayed adoption of CE initiatives. Strategic communication that leverages past successes and emphasizes readiness for future challenges can help shift stakeholders from reactive to proactive engagement (Arvai et al., 2012).

To overcome these cognitive barriers, a multifaceted approach is essential. Educational campaigns can address misconceptions and promote long-term sustainability benefits, while financial and policy incentives can encourage early adoption of CE practices. Positive framing that highlights innovation and value creation can reshape stakeholder perceptions and motivate action. By addressing these biases, businesses and policymakers can foster meaningful stakeholder engagement, creating a conducive environment for CE adoption and advancing sustainability objectives (Aarikka-Stenroos et al., 2023; Schultz et al., 2024).

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