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Unveiling the Landscape of Circular Economy Patents: A Novel Taxonomy Approach

Discussion paper n. 46/2025

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Unveiling the Landscape of Circular Economy Patents: A Novel Taxonomy Approach*

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Abstract

We propose a novel taxonomy for identifying circular patents, focusing on 75,667 patents filed by Italian firms and granted by the European Patent Office between 1997 and 2019. The methodology combines Cooperative Patent Classification and International Patent Classification codes with a keyword-search algorithm, which flags patents as circular if titles or abstracts contain three or more CE-related terms. The algorithm, refined using a sample of 1,000 patents, substantially broadens the scope of circular patents beyond the set of waste patents typically used as a proxy. We analyze the evolution of Italian circular patents, their sectoral, geographical, and technological distributions, and the network of keywords found in their titles and abstracts.

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1 Introduction

The transition to a circular economy (CE) presents a promising pathway to simultaneously address two of the most pressing global challenges of our time: mitigating climate change by reducing greenhouse gas (GHG) emissions and curbing unsustainable material consumption while fostering strategic autonomy.

On one hand, tackling climate change requires ambitious reductions in GHG emissions. Material production and consumption play a central role in this endeavor, as material extraction, handling, and use contribute approximately 70% of global GHG emissions (Circle Economy, 2021). On the other hand, the current pace of material consumption is unsustainable given Earth's finite resources. Global material extraction has already more than tripled since 1970 and has experienced a significant acceleration since 2000 (International Resource Panel, 2019). Projections for the future are equally concerning: mineral demand for the clean energy transition is expected to surge dramatically by 2040 or 2050, raising the risk of severe supply-demand imbalances (International Resource Panel, 2024).

By prioritizing reuse, recycling, and the efficient use of resources, CE strategies can simultaneously reduce material extraction and mitigate GHG emissions. Implementing circular practices can help decouple economic growth from resource use and its dependency on raw materials. Additionally, they can create sustainable value chains by decreasing import dependency for critical raw materials (Månberger, 2023) and minimizing environmental harm. Thus, a transition to a CE is not only an environmental necessity but also an opportunity to foster a resilient and sustainable future.

To advance the shift to a net-zero economy, achieve ambitious sustainability and environmental protection goals, and secure its strategic autonomy, the European Union (EU) has fully committed to the transition to a CE. On one hand, the New Circular Economy Action Plan serves as a key instrument to fulfill the objectives of the European Green Deal and the emissions reduction targets outlined in the Fit for 55 package, promoting long-term sustainability and GHG reductions. On the other hand, the CE transition has been embedded as a central sustainability objective within the European Taxonomy Regulation (European Parliament, 2020). This framework not only establishes a unified EU definition of the CE but also provides a foundation for channeling sustainable investments and aligning financial flows with circular innovations and practices. Furthermore, enhanced circularity has been identified as a vital strategy for reducing dependencies on critical raw materials, thereby reinforcing the EU's economic resilience and strategic autonomy (European Commission, 2023; Mathieux et al., 2017).

Given the critical role of the transition to a CE in addressing pressing global challenges and its prominence within the EU policy framework, monitoring progress toward a CE becomes imperative. Accurate tracking enables the identification of areas requiring urgent action and highlights sectors or regions where advancements are most needed.

Achieving this necessitates the development and use of precise and comprehensive indicators, capable of capturing the multifaceted nature of circular practices and trajectories. However, existing metrics in scientific literature often only account for specific components of circularity, such as recycling, while the multifaceted nature of circular innovations calls for a more comprehensive taxonomy. Furthermore, many currently employed indicators are designed to assess present performance — such as recycling rates or material consumption — yet they fall short in their ability to anticipate or predict future trends and potential advancements in circularity.

An alternative approach to measuring the transition towards a CE focuses on the development and diffusion of circular innovations. Within this context, patents are crucial for examining and forecasting the trajectory of CE developments. Patents represent technological innovations and serve as indicators of future market trends and areas of investment. Analyzing patent activity provides insights into research and development directions, identifies emerging technologies, and highlights potential collaboration and investment areas in CE.

Despite the recognized importance of patents in shaping the CE landscape, a critical gap persists due to the lack of a standardized classification system for circular patents. This absence hampers the ability of researchers, policymakers, and industry stakeholders to accurately assess the scope, impact, and evolution of circular innovations. Without a clear taxonomy, tracking advancements in circular technologies and informing targeted interventions becomes significantly more challenging.

To bridge this gap, we introduce 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 principles.

Focusing on the case of Italian patents, our methodology identifies a broader and more comprehensive set of circular patents than traditional approaches, which often rely solely on waste patents as a proxy. Our findings underscore the distinctiveness of circular patents compared to green patents, highlighting their unique contributions to the innovation landscape. Additionally, we explore the sectoral and geographical distribution of circular patents in Italy and identify the technological fields most strongly associated with circular practices.

These analyses represent a first step towards understanding the circular innovation landscape and identifying pivotal technological drivers and adopters, enabling the assessment of broader economic ramifications of the CE transition.

The remaining part of the paper is structured as follows. In Section 2 we provide a review of the relevant literature, in Section 3 we illustrate the methodology developed to identify circular patents, and in Section 4 we report an application of the methodology to the landscape of Italian patents. Finally, in Section 5 we conclude and discuss potential applications of the proposed methodology.

2 Literature Review

The growing importance of the CE paradigm is reflected in the extensive literature aimed at defining it and identifying its key characteristics (Geisendorf and Pietrulla, 2018; Korhonen et al., 2018; Reike et al., 2018; Kirchherr et al., 2017; Ghisellini et al., 2016).

According to Nobre and Tavares (2021), a comprehensive definition of CE is as follows: "Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environmental extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in the case of a treated organic residual, safely back to the environment as in a natural regenerating cycle."

This definition identifies the core essence of CE as an economic model focused on minimizing waste and pollution across the entire life-cycle of materials. Notably, the emphasis on materials rather than products highlights the broader scope of CE, stressing the importance of materiality and the need to extend the life-cycle of materials beyond their use in a single product.

Alongside this effort to define the CE, there has been a notable proliferation of circularity measures. These metrics span a wide spectrum, addressing different scales of analysis—from macro-level assessments of countries and regions to micro-level evaluations of firms and specific products (Moraga et al., 2019; Saidani et al., 2019). This diversity reflects the complexity and multidimensional nature of circularity but also underscores the need for alignment and consistency in measurement approaches. Without standardized frameworks, comparing circularity performance across different entities or levels remains a significant challenge, hindering a cohesive understanding of progress toward a CE.

The EU Circular Economy Monitoring Framework (Eurostat, 2023) provides country-level data on CE indicators, encompassing production and consumption, waste management, secondary raw materials, competitiveness and innovation, global sustainability, and resilience. However, as noted by Pacurariu et al. (2021), these indicators often exhibit a predominant focus on waste-related aspects. Similarly, ESPON (2019) offers a territorial perspective, estimating regional performance across indicators like changes in domestic material consumption, waste generation per capita, and turnover of CE business models. Overall, macro-level indicators have proven valuable for cross-country comparisons, enabling the assessment of both circularity levels, preparedness to the transition to a CE, and evolving trends over time (Mazur-Wierzbicka, 2021; Momete, 2020; Silvestri et al., 2020).

One of the first proposals for developing standardized circular indicators at the company level was supported by Ellen MacArthur Foundation (2015), focusing on metrics related to input in the production process, utility during use, destination after use, and recycling efficiency. Other commonly used firm-level metrics are the Circular Transition Indicators, the Circularity Gap Metric, and Circle Assessment (Circle Economy and Platform for Accelerating the Circular Economy, 2020).

While firm-level indicators can offer precise insights into a company's efforts to adopt circular practices, their broader adoption remains limited due to the lack of readily available and accessible data. A promising approach to achieving scalable metrics on firms' circularity is through the analysis of patent data, which can serve as a proxy for innovation and technological progress in circular practices. However, the absence of a unified framework for identifying circular patents poses a significant challenge. Furthermore, existing approaches often fail to account for the multidimensional nature of circular technologies, resulting in fragmented and incomplete analyses (Venugopalan and Rai, 2015). These limitations currently hinder the effective use of patent data for conducting comprehensive assessments of circularity.

Circular patents have primarily been identified using codes from the Cooperative Patent Classification (CPC) and International Patent Classification (IPC) systems, focusing especially on technology classes related to waste treatment and recycling (Portillo-Tarragona et al., 2024; Fusillo et al., 2021; Hysa et al., 2020; Marino and Pariso, 2020). Following this approach, Valero-Gil and Scarpellini (2024) study whether circular innovations improve firms' environmental performance.

An alternative approach for identifying circular patents involves text analysis techniques to extract insights from titles and abstracts. Text analysis is scalable and efficient for identifying relevant patents and uncovering trends and patterns within patent datasets. One strategy involves using keywords (Gerdsri and Teekasap, 2022; Venugopalan and Rai, 2015), such as terms from the 10R framework (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover). Focusing on the battery sector, Metzger et al. (2023) identify circular patents as those patents containing at least one keyword from a pre-specified set.

However, the use of keywords for patent classification can be inaccurate: spelling mistakes in patent descriptions may exclude relevant patents, and the everyday use of 10R words can include non-circular patents. To overcome these issues, combining the keyword approach with CPC/IPC classifications is recommended (Popp et al., 2011; Dechezleprêtre et al., 2011). This combined methodology restricts the search to patents in selected economic sectors, reducing the likelihood of false positives while aiming to capture the entire universe of circular patents. Modic et al. (2021) suggest the integration of additional data sources, such as citations, inventor names and locations, to further validate the set of patents retrieved via keywords-search.

3 Methodology

We present a methodology for developing a taxonomy of circular patents that utilizes both the technological classifications of patents and the information contained in their titles and abstracts.

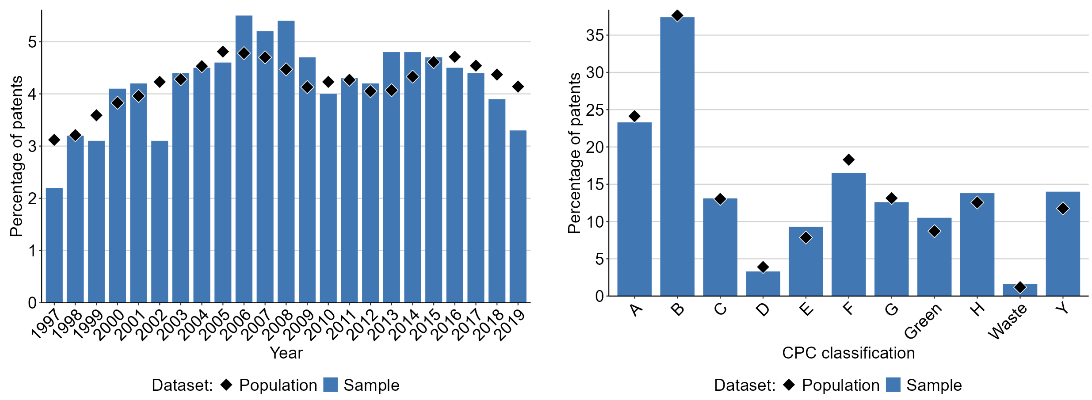
Our methodology is structured around three core blocks. The first block consists of a patents dataset containing at least information related to their title and abstract together with their CPC and IPC codes. The second block consists of a set of keywords retrieved from multiple sources. The third block is represented by a keyword-search algorithm. This algorithm is designed to identify a patent as circular if either the patent is related to wastewater treatment and waste management (from now on simply waste) technologies according to either its CPC or IPC codes or if its title and abstract contain a minimum threshold of relevant keywords.

We then evaluate the performance of the algorithm on a sample of patents manually reviewed and classified as either circular or non-circular based on predefined criteria.

3.1 Patent data and manual classification

We utilize patent data from the 2023 Spring edition of PATSTAT, which offers a comprehensive dataset including bibliographic details, standardized patent technology classifications, and applicant information. Our analysis focuses on patent granted to Italian firms at the European Patent Office (EPO) between 1997 and 2019, encompassing 75,667 patents submitted by approximately 15,000 companies.

To test, optimize, and evaluate the algorithm, we randomly extract a sample of 1,000 patents from the reference population of Italian patents. We carefully construct the sample to preserve the same distribution by year and technological class as the reference population, as illustrated in Figure 1.



(a) (b)

Fig. 1: Comparison of the composition of the extracted patent sample with the reference population of Italian patents, based on earliest filing year (a) and CPC technological classes (b).

We then review and manually classify the patents in the extracted sample as either circular or non-circular. This classification is based on predefined criteria aimed at identifying patents that potentially contribute to the transition towards a CE.

We develop these criteria by drawing on relevant literature that defines the CE (Nobre and Tavares, 2021; Kirchherr et al., 2017; MacArthur et al., 2013), and outlines strategies for promoting this transition (Chrispim et al., 2023; Uvarova et al., 2023; Taranic et al., 2016), as well as the European Taxonomy Regulation (European Parliament, 2020), which specifies economic activities that align with the objective of advancing a CE.

The resulting criteria specify that, to potentially contribute to a transition towards a CE, a technology should fulfill at least one of the following conditions:

a. improve resource efficiency by minimizing resource use or optimizing production processes;
b. extend product longevity through enhanced durability, reparability, upgradability, or reusability;
c. prolong product usage via reuse, repurposing, disassembly, remanufacturing, upgrading, repairing, or sharing;
d. reduce waste generation or improve waste management practices;
e. introduce innovation in material use, such as employing biodegradable or recycled materials; or
f. implement eco-design principles, including modularity, design for longevity, design for disassembly, and minimizing the environmental impact across the entire product life cycle.

This definition closely aligns with the European Taxonomy Regulation but deliberately excludes enabling activities - those activities (in our context, patents) that, while not circular

Source	Keywords
CE framework	circular, durability, duration, efficiency, lifecycle, lifespan, lifetime, long-lasting, optimization, predictive maintenance, recover, recycle, reduce, refurbish, refuse, regenerate, remanufacture, renewable, repair, repurpose, restore, rethink, reuse, secondary materials, take-back, upcycle
Waste patents	acidogenesis, anaerobic, biodegradable, biodiesel, biofuels, biogas, biogenic, biologic, biomass, bioreactors, bioremediation, carbon dioxide, carbon sequestration, carbon capture, comminuting, compacting, composting, decay, decomposition, decontamination, deinking, digesters, disposal, earthworm, electrochemical cell, emissions, epoxidized vegetable oil, fermentation, filter, fractionation, gasifier, geopolymer concrete, guayule shrubs, hempcrete, lignocellulose, manure, material flow management, methanization, methanogenesis, microfibrillated cellulose, microfiltration, miniaturization, nanocellulose, natural fertilizer, organic, pasteurization, pressurization, purification, re-feed, removal of pollutants, replenish, repulpable, reutilization, separation, sewage, shrink, sludge disintegration, ultrafiltration, waste, water treatment
IEA database	absorption, battery shredding, bio-coal, bio-energy, bio-ethanol, bio-kerosene, bio-methane, bio-oil, bio-photolysis, bio-refinery, bio-synthetic, carbon substitution, concentrated solar power, conversion, disassembly, dynamic line rating systems, fuel cell, gasification, green hydrogen, hydrogenated vegetable oil, hydrothermal liquefaction, latent heat storage, leaching, liquid direct air capture, molten oxide electrolysis, multipurpose, ocean thermal energy conversion, photovoltaics, platooning, reconfigurable, rejuvenation, remediation, reprocess, salinity gradient, solar tower, sustainable, thermochemical splitting of co2, tidal power, transactive energy, ultrasonic separation, upgrading of micro-algae, wave energy converters, wind energy, wind turbine

Table 1: Initial set of keywords by source.

on their own, support the development of circular technologies. This exclusion reflects a limitation in our algorithm, which analyzes patent titles and abstracts and may not reliably determine whether a patent fulfills an enabling role[1].

By applying these specified criteria to the manual classification of the patents sample, we identify as circular 92 out of the 1,000 sampled patents, corresponding to a 9.2% prevalence.

3.2 Keywords set

We compile the initial keyword set from several sources to comprehensively capture terms relevant to the CE paradigm. This includes core CE-related terms from scientific literature, frequently used CE terms in patents focused on wastewater treatment and waste management, and circular technology keywords from the International Energy Agency's (IEA) green technologies database. We report the complete list of initial keywords in Table 1 divided according to the source from which we have extracted the keyword.

The first group of keywords draws from the scientific literature on the CE paradigm, focusing on the 10R framework, life cycle assessment methodologies, and characteristics that define patents as supporting a transition to a CE, as outlined in Section 3.1.

We derive the second group of keywords from titles and abstracts of waste patents according to their CPC (Veefkind et al., 2012; Angelucci et al., 2018) or IPC codes. More precisely, we identify waste patents and those pertaining to waste management technologies according to at least one among: the EPO Y-tagging system (EPO, 2016), the World Intellectual Property Organization (WIPO) IPC Green Inventory[2], and the Organization for Economic Co-operation and

[1] Nevertheless, the algorithm still allows for the identification of enabling patents through an additional analysis. In fact, to classify a given patent as an enabling patent, one can analyze its forward citations and apply the keyword-search algorithm to those cited patents. If at least one forward citation is classified as circular, the original patent can then be identified as a circular enabling patent.

[2] https://www.wipo.int/classifications/ipc/green-inventory/home.

Development (OECD) ENV-TECH search strategies (Haščič and Migotto, 2015). The three classifications are jointly utilized because they capture distinct aspects of waste-related innovations and have been found to be complementary in coverage (Favot et al., 2023).

Waste patents are recognized in the literature as key to circular practices (Portillo-Tarragona et al., 2024) and thus provide valuable keyword sources. Identifying these keywords involves analyzing the abstracts and titles of patents within these fields using natural language processing to identify and prioritize the most common terms.

Lastly, we use the IEA database to identify terms linked to circular principles within sustainable technology repositories. The IEA database encompasses over 550 technologies contributing to net-zero emissions across the energy sector, each accompanied by a description that we assess for its relevance to CE objectives.

The rationale for using multiple sources to identify CE keywords is to increase the likelihood of accurately capturing circular patents. While keywords drawn from scientific literature are inherently aligned with the CE paradigm, they may be either too broad (such as some terms from the 10R framework) or too specialized, appearing primarily within academic discourse. Adding keywords from other sources addresses these limitations: terms extracted from waste patents incorporate patent-specific language, while keywords from the IEA database contribute the names of specific technologies that may facilitate a transition to a CE.

Before applying the keywords-search algorithm, we manually validate each keyword to ensure relevance, eliminating irrelevant terms and duplicates. We then stem keywords (e.g., "recycle" is stemmed to "recycl-" to capture variations like "recycle," "recycling," and "recycled") and include alternative spellings (e.g., "life cycle" and "lifecycle").

We further refine the initial keywords set through a preliminary keyword search on the manually classified patent sample. In this search, we identify as "predicted circular" patents whose title and abstract contain at least three terms from the initial keywords set.

Comparing the predicted circular patents with those manually classified as circular allows us to identify true positives, false positives, true negatives, and false negatives. We use this comparison to derive two additional sets of keywords using natural language processing techniques.

From the set of false negatives, we extract additional keywords — terms frequently found in manually classified circular patents with technological classifications beyond waste. These keywords span diverse technological areas, broadening the algorithm's capacity to identify circular patents across various fields.

Conversely, we employ false positive patents as a source for stop-words. These stop-words, which reduce the keyword count by one when present, allow the algorithm to deprioritize, but not entirely exclude, patents associated with specific non-circular technologies, such as pharmaceuticals. The use of stop-words also enhances the contextual specificity of keywords; for example, the stop-word "disease" helps prevent the keyword "treatment" from being misclassified as circular in the context of medical applications.

Finally, we refine the sets of keywords and stop-words by analyzing the manually classified patent sample. For each keyword, we calculate its relative frequency in manually classified circular patents versus non-circular patents. We retain only keywords twice as common in circular patents compared to non-circular ones (or less than half as common for stop-words). This criterion ensures that keywords are strongly associated with circular patents, while stop-words are relatively uncommon in them, improving the overall predictive accuracy by filtering out potentially misleading terms.

In Table 2 we report the final set of keywords resulting from these additional refinements.

3.3 Keyword-search algorithm and performance

The keywords-search algorithm identifies as circular two sets of patents. The first set comprises all patents pertaining to waste technologies according to at least one among the EPO Y-tagging system, the WIPO IPC Green Inventory, and the OECD ENV-TECH search strategies. Instead, the second set consists of non-waste patents showing a clear association with CE principles by having in their title and/or abstract at least a certain number of keywords.

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 2: Final set of keywords by source.

We optimize the algorithm's parameters to maximize performance on the manually classified patent sample. Specifically, we test the keyword-search algorithm with different parameter combinations: searching within both title and abstract, only within the title, and only within the abstract, with a keyword threshold ranging from 1 to 5. The results, presented in Figure 2, include for each parameter setting several performance measures: accuracy, precision, recall, F-score, and F-score computed by weighting precision twice as recall (F-score (0.5)).

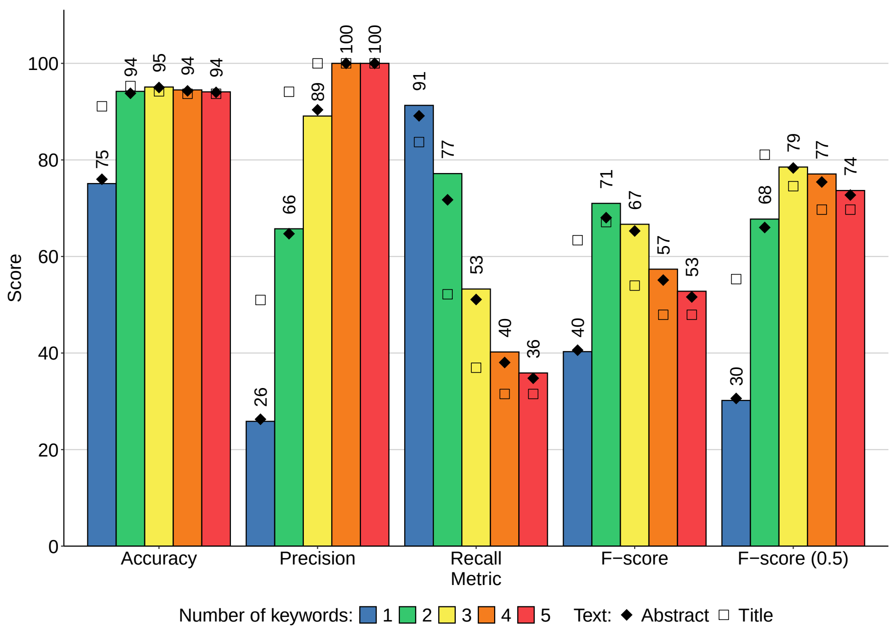


Fig. 2: Comparison of the keyword-search algorithm performance across varying keyword thresholds when applied to both the title and abstract (reference bars and labels), the abstract only (diamonds), and the title only (squares) of each patent.

The keyword-search algorithm generally achieves high accuracy, though this metric is less informative given the low prevalence of circular patents in the sample. Notably, the algorithm's precision sharply improves as the keyword threshold for classifying a patent as circular increases, indicating that the selected keywords are well-targeted. However, as expected, raising the keyword threshold reduces recall.

A threshold of 4 or 5 keywords appears suboptimal: the precision gain compared to a threshold of 3 is minimal, while the recall drop is substantial. Similarly, setting the threshold to just 1 keyword is suboptimal compared to 2 keywords, as the precision loss outweighs the recall gain. Choosing an optimal keyword threshold of 2 or 3 ultimately depends on whether the study prioritizes higher confidence that identified patents are indeed circular or aims to capture a broader set of circular patents. Given our objectives, precision is more critical, leading us to consider a threshold of 3 as optimal.

When comparing results by text field, the algorithm performs similarly when applied to both the title and abstract or to the abstract alone, with the combined approach showing slightly better performance. In contrast, a distinct pattern emerges when the algorithm is applied solely to the title, which is reasonable given that titles are typically much shorter than abstracts. Specifically, when applied only to titles, the algorithm achieves high precision even with a threshold of 2 keywords, but recall rates are consistently lower. Overall, the choice of both title and abstract seems the most appropriate.

Given the previous considerations, the selected version of the keywords-search algorithm identifies as circular patents whose title and abstract combined contain at least three keywords (eventually discounting penalties due to the presence of stop-words). Additionally, waste patents are automatically classified as circular. We summarize the resulting classification procedure in Figure 3.

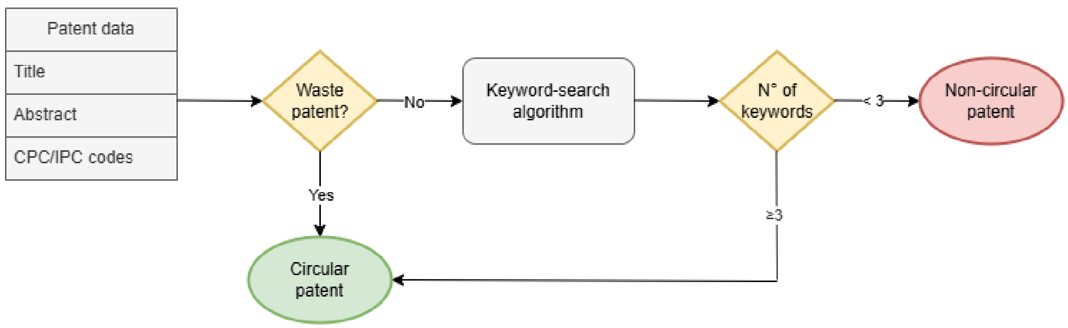


Fig. 3: Flowchart illustrating the complete procedure for classifying patents as circular or non-circular.

4 Application: The landscape of Italian Circular Patents

We apply the keyword-search algorithm described in the previous section to a dataset of 75,667 patent granted to Italian firms at the EPO between 1997 and 2019. This analysis identifies 3,372 patents as circular, accounting for approximately 4.46% of the dataset. In comparison, using waste patents as a proxy for circular innovation would identify only 1,490 (1.97%) patents. Thus, the keyword-search algorithm reveals 1,882 additional circular patents - a substantial increase of approximately +126%. Furthermore, waste-related patents constitute around 44.19% of the identified circular patents, underscoring that relying on waste patents as a proxy significantly underrepresents the broader scope of circular innovation.

Among the circular patents, around 2,227 (roughly 66%) are also classified as green patents based on their technology classifications[3] and more than half of these overlapping patents are

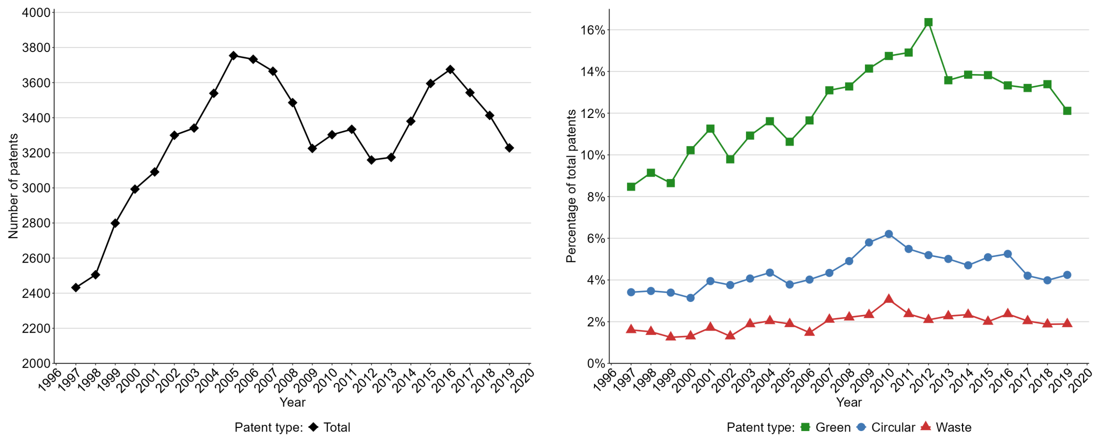
[3]Following the approach used for waste patents, we define green patents as those classified as such by at least one of the following: the EPO Y-tagging system, the WIPO IPC Green Inventory, and the OECD ENV-TECH search strategies.

categorized as waste patents. This limited overlap between the sets of circular and green patents underscores the importance of a distinct classification framework for circular patents.

In the next subsections, we analyze the distribution of Italian circular patents based on their earliest filing year, the applicant's location at NUTS 2 and NUTS 3 levels, and the associated economic sectors. Furthermore, we utilize patents' CPC and technical field codes[4] to identify both the most frequently occurring codes among circular patents and the codes with the highest circularity across all patents. Finally, we extract the most commonly used keywords from circular patents titles and abstracts, exploring their interconnections.

4.1 Temporal and Geographic Distribution of Circular Patents

In Figure 4 we illustrate total Italian patents together with the percentage of green, circular and waste patents from 1997 to 2019.



(a) (b)

Fig. 4: Total number of Italian patents (panel (a)) and the percentage of green, circular, and waste patents (panel (b)) by year, 1997–2019.

As shown in panel (a), the total number of patents grew significantly until 2005, rising from 2,400 to nearly 3,800 per year. Since then, patent filings have fluctuated between 3,200 and 3,800 annually, with periods of decline followed by recoveries.

Panel (b) shows that the percentage of circular patents rose from 3.41% (83 patents) in 1997 to a peak of 6.21% (205) in 2010, before declining to 4.24% (137) by 2019. Green and waste-related patents follow a similar trajectory, though the fluctuations are more pronounced for green patents and more gradual for waste patents. Additionally, the increasing share of circular, green, and waste patents over time indicates that these types of patents have, on average, grown at a faster rate than total patents. However, this gap has narrowed in the most recent years of analysis.

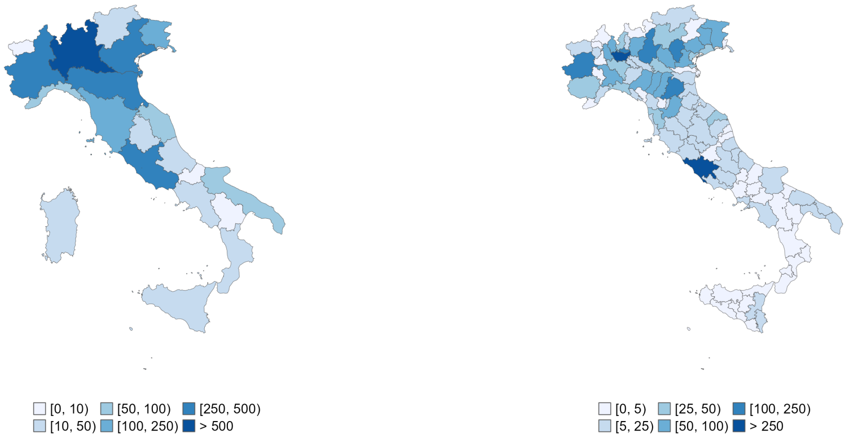
The geographical distribution of circular patents, as illustrated in Figure 5, reveals a notable concentration in the Northern regions of Italy.

Focusing on the regional distribution (panel (a)) Lombardy alone counts 1,217 circular patents, representing nearly 36.09% of all Italian circular patents. Together, the top five regions – Lombardy, Piedmont (428 patents), Emilia-Romagna (428), Veneto (385) and Lazio (289) – account for over 81% of circular patents, whereas the Southern and Insular regions collectively contribute about 4.38%. However, when considering the percentage of circular patents relative to total regional patents, a different pattern emerges. Southern regions tend to have higher percentages of circular patents though this might be driven by their low number of total and circular patents.

[4] Technical fields consists of 35 aggregates of IPC codes aggregated according to the WIPO IPC technological concordance. For further information, see Schmoch (2008).

Lombardy, which leads in the absolute number of circular patents, is close to the national average in percentage terms (4.33%). Instead, Emilia-Romagna and Veneto slightly underperform with, respectively, 3.35% and 4.02% of circular patents. Notably, Lazio stands out among the regions with the highest number of circular patents by boasting one among the highest percentages of circular patents (around 9.41%) – more than double the national average.

The distribution of circular patents by province, shown in panel (b) of Figure 5, suggests a concentration in areas with significant economic activity and high-density population. Milan, the major economic hub, accounts for 661 circular patents — approximately 19.60% of all Italian circular patents — followed by Rome (261), Turin (215), Bologna (154), and Vicenza (148). Together, these top five provinces account for around 42.67% of circular patents.



(a) Regional distribution

(b) Provincial distribution

Fig. 5: Cumulative number of circular patents by region (panel (a)) and province (panel (b)), 1997-2019.

4.2 Sectoral Distribution of Circular Patents

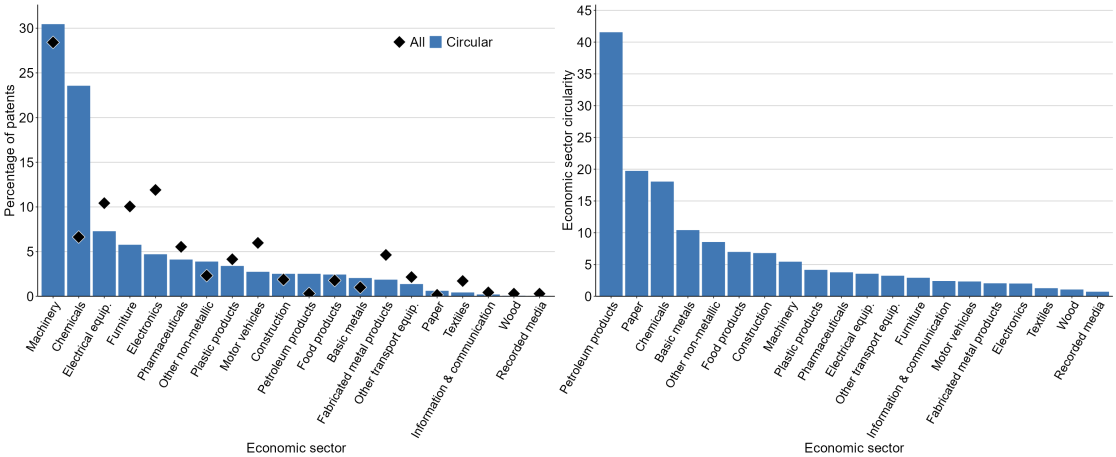
The key findings from the analysis of circular patents by sector of economic activity are presented in Figure 6. This analysis uses the Statistical classification of economic activities in the European Community (NACE) assigned to each patent in the PATSTAT Database.

PATSTAT assigns NACE codes to patents based on their IPC codes, applying the correspondence table between IPC and NACE classifications developed by EUROSTAT (Van Looy et al., 2015). While this mapping exclusively links IPC codes to manufacturing sectors and the assigned NACE code may not always reflect the applicant firm's actual economic sector, it provides valuable insights into the sectors most closely aligned with the patent's knowledge content. This approach helps identify the industries most likely to benefit from the innovation described in the patent.

Panel (a) of Figure 6 displays the top 20 NACE 2-digit economic sectors associated with Italian circular patents[5], along with their representation among all Italian patents. The Machinery sector is the most prevalent, accounting for approximately 30.45% of circular patents, closely aligning with its share of total patents (28.41%). The Chemicals sector follows at 23.56%, significantly overrepresented compared to its 6.63% share of all patents. Next are the Electrical Equipment (7.28%), Furniture (5.77%), and Electronics (4.70%) sectors. Unlike Machinery and Chemicals, these sectors are not only far less common but also notably underrepresented in circular patents relative to total patents. This suggests that their absolute frequency in circular patents is driven

[5]Percentages do not sum to 100%, as a single patent can be linked to multiple sectors.

more by their overall patenting activity than by a high degree of circularity, as illustrated in panel (b) of Figure 6.



(a) Sectoral distribution

(b) Sectoral circularity

Fig. 6: Percentage of circular patents by economic sector alongside the sectoral share in total patents (panel (a)) and sectoral circularity (panel (b)). Both panels highlight the top 20 economic sectors.

In panel (b) of Figure 6 we rank economic sectors by their circularity, measured as the percentage of circular patents within each sector. Petroleum Products stands out as the most circular sector, with 41.55% of its patents classified as circular. This is followed by the Paper sector (19.74%) and Chemicals (18.05%). Sectors related to Metal Products and Food Products also exhibit above-average levels of circularity.

4.3 Technological Classifications of Circular Patents

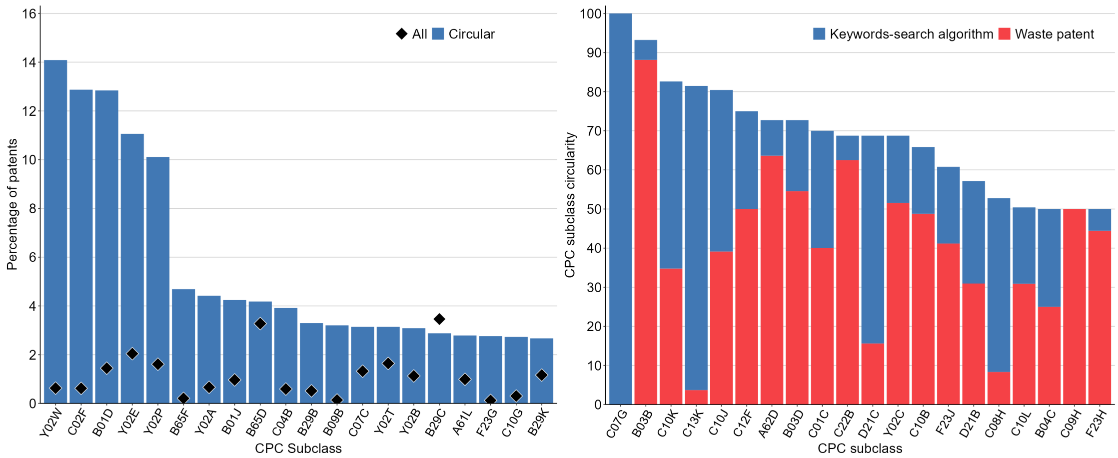
We analyze CPC codes and technical field information from two distinct perspectives. On one hand, we examine the composition of circular technologies by assessing the proportion of circular patents associated with each CPC code or technical field. On the other hand, we aim to identify the most circular CPC codes and technical fields - those with the highest percentage of circular patents relative to the total patents in their respective categories.

Figure 7 presents the analysis focused on CPC codes. Panel (a) highlights the 20 most frequent CPC codes linked to circular patents[6] together with their prevalence in total patents.

The most prevalent CPC code among circular patents is Y02W (Climate Change Mitigation Technologies related to Wastewater Treatment or Waste Management), appearing in approximately 14.09% of cases. Other frequently occurring CPC codes include C02F (Treatment of Water, Wastewater, Sewage, or Sludge) at 12.87%, B01D (Separation) at 12.84%, Y02E (Reduction of Greenhouse Gas Emissions related to Energy Generation, Transmission, or Distribution) at 11.06%, and Y02P (Climate Change Mitigation Technologies in the Production or Processing of Goods) at 10.11%. These are the only CPC codes associated with at least 5% of circular patents. The figure further highlights that circular patents are significantly more concentrated in specific CPC subclasses with respect to total patents.

Overall, looking at CPC Sections[7] Y-tags and CPC codes within Section B (Performing Operations; Transporting) are the most prevalent in circular patents.

[6]Percentages do not sum to 100 because a single patent can be associated with multiple CPC codes.
[7]The CPC features the following Sections: A = Human necessities; B = Performing operations; transporting; C = Chemistry; metallurgy; D = Textiles; paper; E = Fixed constructions; F = Mechanical engineering; lighting; heating; weapons; blasting engines or pumps; G = Physics; H = Electricity; Y = General tagging of new technological developments. The first letter of each Subclass code corresponds to the Section to which the patent belongs to.



(a) Distribution by CPC codes

(b) CPC codes circularity

Fig. 7: Percentage of circular patents by their CPC code classification alongside the frequency of CPC codes in total patents (panel (a)) and CPC code circularity categorized by the source that identified the patent as circular (panel (b)). Both panels highlight the top 20 CPC codes.

Panel (b) of Figure 7 examines the circularity of individual CPC codes. The figure further differentiates between circularity driven by patents classified as circular due to their relevance to waste technologies and circularity identified through the keyword-search algorithm.

Notably, in the panel we deliberately exclude eight CPC subclasses that are inherently 100% circular. This is because, according to at least one among the EPO Y-tags, the WIPO IPC Green Inventory, and the OECD ENV-TECH search strategies, the entire subclass is classified as belonging to waste technologies. These excluded subclasses are B09B (Disposal of solid waste not otherwise provided for), B09C (Reclamation of contaminated soil), B65F (Gathering or removal of domestic or like refuse), C02F (Treatment of water, waste water, sewage, or sludge), C05F (Fertilisers from waste or refuse), E03F (Sewers; cesspools), F23G (Cremation furnaces; consuming waste products by combustion), and Y02W (Climate change mitigation technologies related to wastewater treatment or waste management).

By looking at panel (b) of Figure 7 we observe full circularity for C07G (Compounds of Unknown Constitution), though this classification applies to only a single patent in the dataset. The next most circular CPC code is B03B (Separating Solid Materials Using Liquids or Pneumatic Tables or Jigs) followed by four codes within the Chemistry section: C10K (Purifying or modifying the chemical composition of combustible gases containing carbon monoxide), C13K (Saccharides obtained from natural sources), C10J (Production of producer gas, water-gas, synthesis gas), and C12F (Recovery of by-products of fermented solutions). Circular patents account for at least 75% of the patents classified under each of these subclasses.

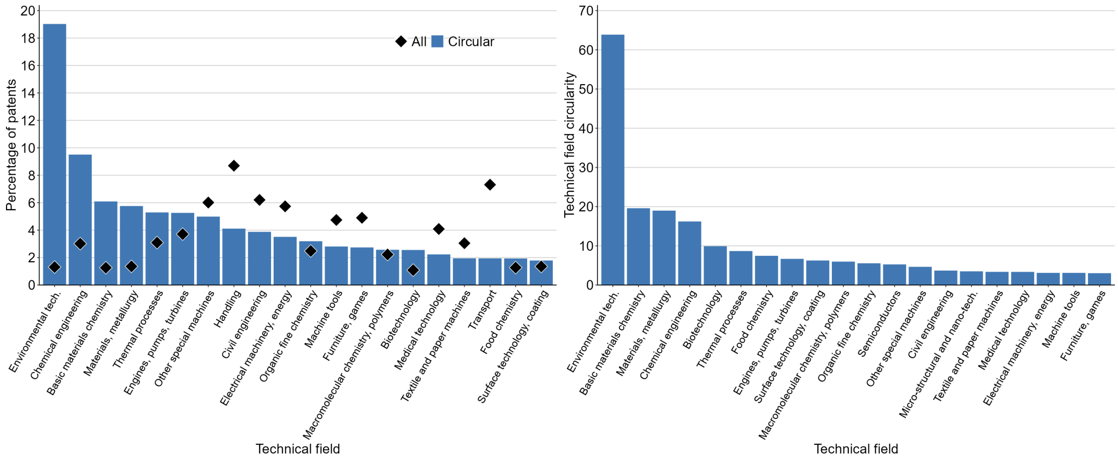
These findings suggest that these CPC codes could serve as a useful starting point for expanding the set of waste patents in attempts to classify patents as circular or non-circular primarily via technological classification codes.

The breakdown by source according to which patents have been identified as circular highlights the strong complementarity between the identification via IPC/CPC codes and the one performed via the keywords-search algorithm. Using only one of the two would not only identify a lower number of circular patents, but would also bias the identified sample by significantly under-representing certain technology classes relevant to the transition towards a CE.

To gain a broader understanding of the technologies most associated with circularity, in Figure 8 we analyze technical fields.

Panel (a) presents the top 20 most frequent technical fields in circular patents, alongside their corresponding representation in the entire set of Italian patents. The "Environmental technologies" field is associated to approximately 19.03% of circular patents, followed by "Chemical

Engineering" (9.51%) and "Basic materials chemistry" (6.09%). The panel underscores the prominence of environmental technologies, as well as technologies related to materials and chemistry, among circular patents. These technical fields are notably overrepresented in circular patents compared to their share in the overall patent dataset.



(a) Distribution by technical field

(b) Technical field circularity

Fig. 8: Percentage of circular patents by technical field alongside the technical field share in total patents (panel (a)) and technical field code circularity (panel (b)). Each panel highlights the top 20 technical field codes.

Panel (b) of Figure 8 reports technical fields circularity, calculated as the percentage of circular patents in the technical field. The most circular technical field is by far the one of "Environmental technologies" with about 63.87% of its patents being classified as circular quite in line with the percentage of circular patents classified as green patents. The following most circular technical fields are "Basic materials chemistry" (19.59%), "Materials, metallurgy" (18.98%), and "Chemical engineering" (16.21%).

4.4 Analysis of Circular Patents Keywords

Finally, we analyze the most frequent keywords found in Italian patents and the keywords network among circular patents. These analyses provide valuable insights into the performance of the keyword-search algorithm and offer additional information about the characteristics and focus areas of circular patents.

In Table 3 we report the top 10 most frequent keywords in the set of Italian patents considered. These include "treatment", "separation", "reduce", "water" and "filter". The table further reports the percentage of total and circular patents whose title and abstract contain each keyword together with the relative frequency with which the keyword is found in circular patents with respect to non-circular ones. As the figures show keywords are significantly more frequent in circular patents, while the opposite occurs for stop-words highlighted in red. This indicates that the keywords-search algorithm works as expected.

In Figure 9 we examine the interconnections between keywords found in circular patents.

The analysis is based on the output of the keyword-search algorithm, which identifies the keywords present in the title and abstract of each circular patent. Using this information, we construct a keywords co-occurrence matrix. This square matrix lists keywords along both rows and columns, with each entry representing the number of circular patents in which the row keyword and the column keyword appear together (i.e., they co-occur).

Leveraging the keywords co-occurrence matrix we construct a weighted network of keywords, where two keywords are connected if they co-occur at least once, and the strength or weight

Keyword	Patents with keyword	Patents with keyword, %	Circular patents with keyword, %	Relative frequency in circular patents
Treatment	5,025	6.64%	24.97%	3.76
Separation	4,174	5.52%	21.41%	3.88
Reduce	3,241	4.28%	15.51%	3.62
Water	3,105	4.10%	23.46%	5.72
Filter	2,195	2.90%	16.07%	5.54
Pharma	2,038	2.69%	0.39%	0.14
Dispenser	2,037	2.69%	1.16%	0.43
Collect	1,960	2.59%	15.69%	6.06
Emissions	1,763	2.33%	5.66%	2.43
Energy	1,720	2.27%	14.83%	6.52

Table 3: Most frequent keywords in the set of Italian patents. Stop-words in red.

of their connection corresponds to the number of circular patents in which they co-occur. We then analyze this weighted network by maximizing clustering modularity and, thus, obtaining the optimal clustering of keywords.

In Figure 9 we depict the resulting keywords clusters via a matrix, with each cell indicating the strength of the link between the corresponding row and column keywords. Connections within the same cluster are shown in cluster-specific colors, while connections between keywords from different clusters are depicted in dark gray. Stronger connections between keywords are represented by cells with higher opacity levels, providing a clear view of the relationships and clustering patterns.

The figure reveals four distinct clusters of keywords. The first cluster, highlighted in yellow, focuses on energy, emissions, and efficiency (energy-efficiency cluster). The second cluster, highlighted in violet, is centered on wastewater treatment and waste management (water-waste cluster), containing keywords such as “waste”, “water”, “treatment”, “filter”, “separation”, “recycle”, and “recover”. The third cluster, shown in green, pertains to organic materials (organic cluster) and includes terms like “bio”, “composting”, “organic”, and “degradable”. Finally, the last cluster in red contains medical terms (med cluster): “pharma”, “medical”, “sterilization”, “preserve”.

Notable interconnections between clusters are observed, indicating shared concepts across these thematic areas.

Both the energy-efficiency and the water-waste clusters exhibit a clear core-periphery structure. This is particularly evident in the water-waste cluster, where the core consists of the keywords - following the order in which they appear in the matrix - from “recover” to “separation”. These core keywords are strongly interconnected within the cluster and also maintain significant links with key terms from other clusters. In contrast, peripheral keywords within the water-waste cluster, the ones from “abatement” to “wash”, tend to have strong connections to at least one core keyword in their cluster but exhibit few and weaker links with other peripheral or cross-cluster keywords.

A similar core-periphery structure is observed in the energy-efficiency cluster, where terms from “circular” to “energy” form the core, while the remaining keywords are more peripheral.

In contrast, the organic and the med clusters show a less distinct hierarchy. A few keywords in the organic cluster, such as “organic”, “bio”, and to a lesser extent “natural” and “biomass”, and only “sterilization” in the med cluster emerge as the most relevant. However, these keywords are not as strongly interconnected compared to the cores of the two other clusters.

Interestingly, many terms commonly associated with the CE framework in the literature — such as those related to the 10R framework — emerge as core keywords across the identified

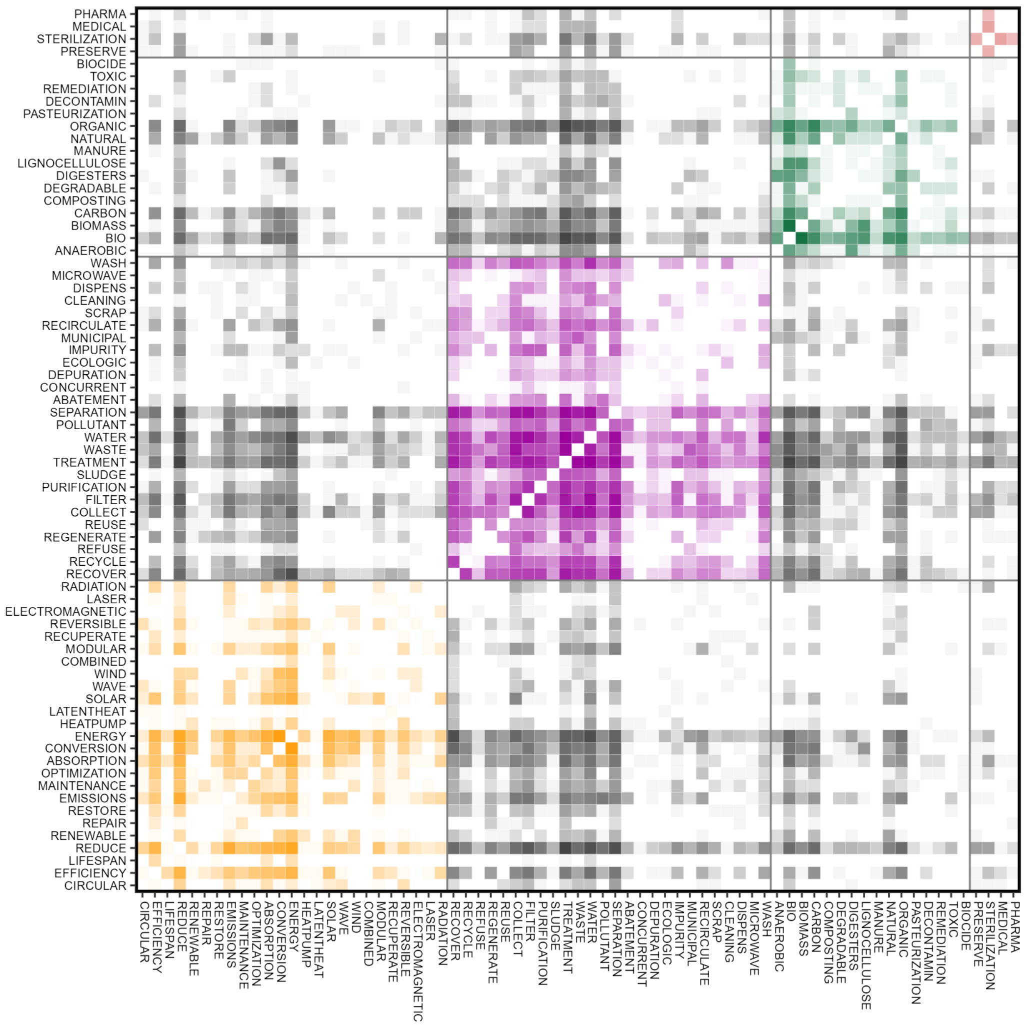


Fig. 9: Optimal clustering of the network of keywords found in circular patents titles and abstracts. Each cell opacity highlights the strength of the link between the corresponding row and column keywords.

clusters. This highlights their centrality and significance within the broader landscape of circular innovation.

5 Discussion

In this paper, we have proposed a novel methodology for developing a taxonomy of circular patents by leveraging patents' IPC/CPC codes alongside the information in their titles and abstracts. According to this approach, we classify a patent as circular if it pertains to waste technologies based on its CPC/IPC codes or if its title and abstract include at least three keywords from a carefully curated set.

We derived the keywords set through an optimization procedure. This process began with an initial pool of terms collected from various sources, including CE concepts emphasized in the scientific literature, common terms associated with circular practices found in waste patents titles and abstracts, and circular-related terminology in the IEA Green Technologies Database. We then refined this initial set through testing on a validated sample of 1,000 patents. We examined titles and abstracts of circular patents not initially classified as such (false negatives) to identify additional keywords, while we analyzed misclassified non-circular patents (false positives) to develop a list of stop-words — terms that, when present, reduce the keyword count by one. We also removed keywords with insufficient relative frequency in circular patents compared to non-circular patents. Finally, we performed a comprehensive manual validation of all keywords to ensure their relevance to the CE paradigm.

After finalizing the set of keywords, we applied the keyword-search algorithm to the validated sample of patents under various parameter configurations. We tested the algorithm on three textual information: both the patent title and abstract, the title only, and the abstract only. Additionally, we evaluated different threshold keyword counts, ranging from 1 to 5, to determine the optimal criteria for classifying a patent as circular.

This analysis allowed us to identify the optimal configuration as the algorithm applied to both the title and abstract with a keyword count threshold of 3. Under this setup, the algorithm achieved an accuracy of 95%, a precision of 89%, and a recall of 53% when tested on the manually validated sample, highlighting its robustness and reliability for identifying circular patents.

We applied the presented methodology to the entire set of Italian patents granted at the EPO between 1997 and 2019, consisting of 75,667 patents. The resulting set of circular patents contains 3,372 patents, representing about 4.46% of the total number of Italian patents within the considered time frame. The implementation of the keyword-search algorithm significantly expands the set of circular patents beyond those identified solely by CPC and IPC codes related to waste technologies – a common approach in the literature. Our method increases the number of identified circular patents from 1,490 to 3,372 – an approximate 126% increase.

After identifying the Italian circular patents registered during the study period, we analyzed their key characteristics. The time series of circular patents reveals a notable increase in registrations between 1997 and 2010, followed by a slight decline over the subsequent decade. Geographically, circular patenting activity is highly concentrated in the Northern regions and Lazio, with the top five regions accounting for over 81% of all circular patents.

The analysis of circular patents by sector of economic activity shows that more than half are linked to the Machinery and Chemicals sectors. Instead, when sectors are ranked by their level of circularity, Petroleum Products, Paper, and Chemicals emerge as the most circular sectors.

We have further analyzed the CPC and technical field classifications of circular patents. The analysis of CPC codes reveals that the majority of Italian circular patents are associated with Y02 tags or Section B (Performing Operations; Transporting). Additionally, this analysis allowed us to identify specific CPC codes that could serve as a foundation for identifying circular patents based on technological classifications rather than keywords. In contrast, the examination of circular patents technical fields underscored the significant role of Environmental Technologies in circular innovation.

Lastly, using data from the keywords found in circular patents titles and abstracts, we constructed a network of keywords and performed a cluster analysis that has revealed four distinct keywords clusters: one focused on energy and efficiency, another centered on wastewater treatment and waste management, a third associated with organic materials, and a last one related to medical terms. This analysis also identified cross-cutting terms that serve as key connectors, linking the entire keywords network and highlighting shared themes across clusters.

The developed taxonomy of circular patents can be further employed in additional analyses. A natural extension would be the replication of the study to other countries to gain a more comprehensive understanding of the global landscape of circular patents and to perform cross-country comparisons. Additionally, one can focus on the potential impact that the patenting activity may have on the CE at the regional level (i.e. waste and recycling statistics, creation of jobs in the CE value-chain, and water footprint reduction). Finally, an input-output analysis applied to sectors exhibiting high circularity levels could shed light on the broader economic implications of circular innovations on related industries and the overall economy.

By extending the analysis to the network of patent citations, it would also be possible to identify crucial interconnections for enabling technologies as well as potential adopters of circular technologies. This avenue of research could extend the scope of the study to encompass innovation spillovers between technological domains and to quantify how much circular patents contribute to other fields' progress and how much they depend on other domains' developments.

The developed taxonomy represents a first step toward addressing several important issues: understanding how a transition to a CE can contribute to CO2 reduction and meeting net-zero targets, evaluating how such a transition can improve firms' performance and boost their investments, and determining the role of a CE – particularly the large-scale adoption of reuse and recycling principles – in enabling the EU to achieve strategic autonomy regarding critical raw materials.

The performed analyses allow for a deeper understanding of the CE innovation landscape and represent a first step in identifying pivotal technological drivers and adopters and assessing the broader economic ramifications of CE transitions. Such insights will inform strategic decision-making for policymakers, industry stakeholders, and researchers committed to advancing sustainable development and innovation agendas.

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