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Revolutionizing the circular economy through new technologies: A new era of sustainable progress

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ABSTRACT

Nowadays the pace of production and consumption is reaching environmentally unsustainable levels. In this regard, the great technological advances developed in recent years are postulated as a source of opportunities to boost the circular economy and sustainable development. This wide range of possibilities offered by new technologies to create a more sustainable reality has aroused the curiosity and interest of the academic world, especially in recent years. The main objective of this research is to reveal the main challenges and opportunities that arise when incorporating new technologies to the objectives of the circular economy. Regarding to the methodology, this study has been partially supported using bibliometric techniques. The results highlight the transformative role of new technologies, especially blockchain and artificial intelligence, in advancing the circular economy, with particular emphasis on the community and technology integration, ethical considerations, technological synergies, sustainable business models, and the burgeoning bioeconomy. We conclude that new technologies promise enhanced resource efficiency, optimized supply chains, innovative business models, and improved product lifecycle management, offering profound economic and environmental benefits while fostering sustainable consumption and collaborative innovation. However, these opportunities also represent the main challenges to address, such as integrating advanced production methods, ensuring supply chain transparency, overcoming the skill gap, avoiding data centralization, and adapting regulatory frameworks to foster equitable and sustainable growth. These are some of the most important areas for further research, especially those related to the development of employees' technological capabilities and the adaptation of regulatory frameworks, as they are understudied research gaps.

1. Introduction

The 21st century is posing serious challenges to both advanced and developing economies, especially regarding the environmental impact of the current unsustainable production systems and consumption habits (Andersen et al., 2023; Henderson and Loreau, 2023). The current linear economic model, which has underpinned global economic expansion over the last few decades, is proving to be an increasingly unsustainable system, with evident environmental and social repercussions, such as deforestation, soil erosion, overflowing landfills, polluted ecosystems, or the alarming depletion of essential resources, among others (Neves and Marques, 2022; Palazzo et al., 2023). In this vein, the demand for goods and services from an ever-growing world population, now approaching 8

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billion people, exerts a profound pressure on natural resources, which not only has ecological, but also economic and geopolitical implications (Cao et al., 2023; Liu et al., 2023a).

Once abundant raw materials, such as fresh water, rare earth metals and fossil fuels, are seeing their reserves dwindle, leading to market volatility and geopolitical conflicts (Shahzad et al., 2023; Xiong et al., 2023). In this context, the circular economy emerges not only as an alternative to the traditional system, but as an essential paradigm shift, representing a holistic approach to address the numerous challenges of our time, and a blueprint towards a more sustainable, prosperous, and equitable future (Marjamaa and Mäkelä, 2022; Muench et al., 2022; Mukherjee et al., 2023). Generally, circular economy is focused on providing a viable strategy to counteract the environmental challenges by minimizing waste and pollution and fostering healthier and more resilient communities, as well as offering a roadmap to a future marked by prosperity, equity, and ecological balance (Abbate et al., 2023; Elgarahy et al., 2023; De Pascale et al., 2023).

The principles underlying the circular economy, such as reuse, recycling, and regeneration, are postulated as the starting point for the development of innovative solutions to develop a socioeconomic model that decouples growth from resource consumption, guaranteeing supply, stabilizing markets, and reducing dependence on exhaustible raw materials (Neves and Marques, 2022; Bianchi and Cordella, 2023; Charlier and Fizaine, 2023). Furthermore, the alignment of circular economy principles with several of the sustainable development goals designed by the United Nations, such as responsible consumption and production, clean water supply and climate action, underscores the relevance of adopting and integrating circular economy practices for the fulfillment of the commitments set for 2030 (Ogunmakinde et al., 2022; Khajuria et al., 2022; Ortiz-de-Montellano et al., 2023).

Central to this discourse is the role of emerging technologies in shaping, facilitating, and enhancing the principles of circularity, which has important implications that warrant scholarly exploration (Khan et al., 2022; Farahbakhsh et al., 2023; Mondal et al., 2023a). The transition towards a circular paradigm and, especially, an environmentally sustainable production, requires the development of innovations, especially new technologies, that facilitate the circular flow of materials, and generate new employment opportunities in emerging sectors such as recycling, sustainable product design and resource management (Sehnem et al., 2022; Hojnik et al., 2023; Jesus and Jugend, 2023; Schöggl et al., 2023). In this regard, the world is witnessing unprecedented technological advances, with profound implications for the implementation of circular practices across various strata of society, that can reshape economies, industries, and social structures (Böckel et al., 2021; Lei et al., 2023; Liu et al., 2023b; Rusch et al., 2023).

Among them, it is worth highlighting the rise of artificial intelligence and blockchain technology, which portend a transformation through which to make an effective transition towards more sustainable production schemes (Oluleye et al., 2022; Yontar, 2023). The artificial intelligence can favor the optimization in the allocation of resources, improve product life cycle management, transform processes, and predict behavioral patterns, in order to boost the efficiency and effectiveness of recycling and reuse processes of materials that today are discarded as waste, acting as a tool in favor of achieving the objectives pursued by the circular economy (Andeobu et al., 2022; Wilson et al., 2022; Singh and Sarkar, 2023).

The role of artificial intelligence goes beyond the allocation of resources, since it allows the analysis of consumption patterns and calibrate production processes in real time, serving as a bulwark against overproduction and the uncontrolled generation of waste, which would make it possible to adapt production to real demand and move towards a circular production model (Bag et al., 2021; Tsui et al., 2022), while the predictive capabilities of machine learning algorithms may allow industries to anticipate resource needs more accurately and ensure the efficient use of materials (Akkem et al., 2023; Jhajharia et al., 2023; Kafy et al., 2023). Therefore, they can be instrumental in changing production processes, reducing the destructive environmental effects of industry and optimizing the production of goods through machine learning and neural networks (Chowdhury et al., 2023; Ganeshkumar et al., 2023; Soori et al., 2023a).

On the other hand, the advent of blockchain technology, a decentralized ledger system, has revolutionized the management of projects, people and supplies at different levels, guaranteeing an unprecedented level of transparency (El Koshiry et al., 2023; Iranmanesh et al., 2023). In business, this revolutionary technology has different applications, especially in connection with contract validation and product traceability (Alamsyah et al., 2023; Hakkarainen and Colicev, 2023), such as smart contracts, which make it possible to ensure compliance with agreements without the need to involve third parties, while their application to supply chain management makes it possible to verify the traceability of products from their origin to the point of consumption, the phases of their life cycle and their reuse or recycling, which is essential for authenticating recycled materials, ensuring responsible sourcing, and validating the sustainability claims of products (Ahmed and MacCarthy, 2023; Biswas et al., 2023; Cozzio et al., 2023).

Both technologies have the potential to generate significant synergies when combined to drive the circular economy (Elghaish et al., 2023; Truant et al., 2024). On the one hand, artificial intelligence-based insights can be recorded in blockchain ledgers, ensuring that decisions made on the basis of their predictions are transparent and verifiable, which can be relevant in areas such as waste management, where generation patterns can be predicted with the help of artificial intelligence, while blockchain can ensure the traceability of waste streams (Jiang et al., 2023; Gupta et al., 2023; Khan et al., 2023; Naveenkumar et al., 2023). Moreover, the combined use of these technologies can foster the development of collaborative consumption models by matching supply and demand in real time and facilitating secure and transparent peer-to-peer transactions, reducing the need for intermediaries, promoting the efficient use of resources and reducing waste (Ghouri et al., 2023; wael AL-khatib et al., 2023; Zhou et al., 2023). At a governmental level, the integration of these two technologies can provide policymakers with dynamic tools to develop and enforce regulations that promote circular practices, providing real-time data on resource flows, and offering a transparent and immutable record of compliance, which would ensure that regulations evolve along with the changing landscape of the circular economy and that compliance is transparent and verifiable (Chaudhary and Nidhi, 2023; Dewasiri et al., 2023; H. Han et al., 2023; J. Han et al., 2023; Kazachenok et al., 2023).

Nevertheless, while both artificial intelligence and blockchain have been explored in different contexts, there is a research gap in understanding their potential to address the current environmental challenges and drive the circular economy, e.g., how can these technologies be integrated to drive the circular economy forward or what are the challenges and opportunities presented by their implementation? In this regard, addressing these questions is not just academically intriguing but also of paramount importance for industries and governments aiming to adopt a circular model of development. The main objective of this research is to reveal the main challenges and opportunities that arise when incorporating new technologies to the objectives of the circular economy. To achieve this aim, the major players in the academic field at different levels, the most outstanding works, and the international research cooperation relations are identified, and the most relevant research fronts carried out by the literature in recent years on the potential of new technologies to drive the circular economy are unveiled.

The analysis of the research fronts is carried out at three levels: the most frequently used keywords in the literature, a keyword co-occurrence analysis, and a study of the abstracts of each of the peer-reviewed articles, which allows moving forward in the identification of research fronts from a general to a more specific level, offering in a synthetic and clear way the main contributions made, and establishing the most relevant challenges and opportunities in this field. Furthermore, Bibliometrix®, v.4.3 software has been used to carry out this research. At their core, bibliometric techniques leverage quantitative methods to analyze and interpret patterns within scholarly publications, offering a systematic approach that ensures that literature reviews are comprehensive and cover the breadth of knowledge in the field under study.

Our study is anchored in a comprehensive dataset encompassing 890 academic papers written by 3567 scholars across 74 countries, covering the decade from January 1, 2013, to December 31, 2022. These articles garnered a collective 19,340 citations and drew from a bibliographic foundation of 59,051 references. Regarding to the structure, after the previous introduction is developed a brief literature review. In the next section it is elucidated the research methodology and then, it is carried out an in-depth presentation and deliberation of our results. The manuscript ends by outlining the conclusions derived from the analysis carried out, and a reflection on possible limitations and suggestions for further research.

2. Methodology

The Web of Science (WoS) database served as our primary resource for procuring academic papers, primarily due to its limited redundancy and its capability for detailed temporal queries. Its reputation as a dependable academic source is well-established (Dima et al., 2022; Popescu et al., 2022), particularly within the indices of SSCI, ESCI, and SCI-E. To target papers related to the potential of new technologies to drive the circular economy, especially artificial intelligence and blockchain, our search criteria were framed as: "TS = ("circular*" OR "waste management") AND ("new technolog*" OR "artificial intelligence" OR "blockchain"). The scope was confined to peer-reviewed articles released between January 1, 2013, and December 31, 2022, resulting in a compilation of 890 articles.

To refine the selection of relevant studies, we employed the PRISMA framework, which provides a standardized approach to conducting and reporting systematic reviews and meta-analyses, ensuring consistency across studies, and allowing the replication and assessment of the study (Page et al., 2021; Grosseck et al., 2019; Pham et al., 2021; Thukral and Jain, 2021; Fauzi, 2023), and helps in identifying and minimizing potential biases in the review process and avoid overlapping, leading to more reliable search results (Ordanini et al., 2008; Richard et al., 2009).

In this vein, bibliometric methods stand as a robust tool for conducting comprehensive literature reviews which, grounded in quantitative analysis, offer a systematic approach to dissecting the vast corpus of scholarly contributions (Schaer, 2013; Arora & Chakraborty, 2021). One of the primary strengths of bibliometric methods is their ability to provide a macroscopic view of a specific academic domain, enabling researchers to discern overarching trends, dominant themes, and seminal works, as well as excel in

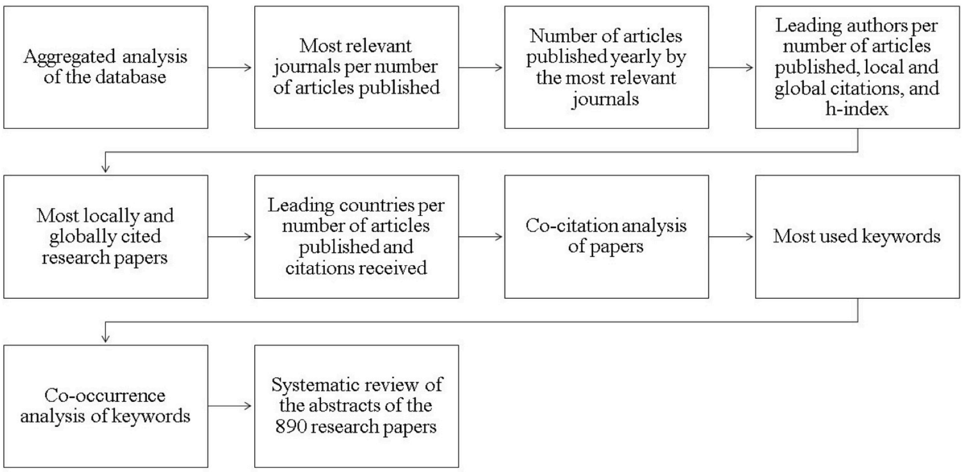

Fig. 1. Review process.

mapping the web of academic collaborations, revealing the interplay between authors, institutions, and countries, thus offering invaluable insights into the dynamics of knowledge production and dissemination (Rousseau, 2014; Kokol and Vošner, 2019; Hao et al., 2021).

Additionally, these techniques are adept at identifying key influencers and thought leaders within a field, thereby guiding researchers towards pivotal contributions, and their versatility ensures their applicability across a wide array of research themes, making them an indispensable asset for scholars aiming to study the ever-expanding academic literature (Li et al., 2017; Pattnaik et al., 2020). Furthermore, the objectivity inherent in these quantitative methods minimizes biases, ensuring a balanced and holistic understanding of the literature, thus offering a confluence of depth, breadth, and precision, elevating the quality and rigor of literature reviews (Paul and Benito, 2018; Hao et al., 2021).

To carry out this research the Bibliometrix® software in its version 4.3 has been used, a tool developed by Aria and Cuccurullo (2017), renowned academics affiliated with the Italian enterprise K-Synth, which is adept at conducting meticulous scientific mapping analyses, presenting results in a visually compelling manner (Goyal and Kumar, 2021). Recognizing the foundational principle that contemporary advancements in a field are often predicated on antecedent scholarly milestones, highlighting a temporal linkage, our research analyzes the potential of new technologies to drive the circular economy by conducting a thorough examination of the content within peer-reviewed articles, complemented by an evaluation of key indicators, such as citation counts, h-index values, and the volume of publications (Hsieh and Chang, 2009). In order to improve readers' understanding, the review process is displayed in Fig. 1.

The data of the academic literature on the potential of new technologies to drive the circular economy displays a picture of a research domain that is growing considerably since 2018, and is characterized by its depth, diversity, and global collaboration. A total of 484 journals have contributed to this discourse, cumulatively publishing 890 articles, having an annual growth rate of 45.05%, indicative of the escalating academic interest and the dynamic nature of this research domain. The exploration of new technologies' potential in driving the circular economy is evidently at the forefront of academic inquiry, promising rich insights and innovative solutions for a sustainable future. The average age of these articles, which is 2.71 years, underscores the recency and contemporaneity of the discussions, while each article, on average, garners 21.73 citations, an evidence of the relevance and impact of the content within the academic community.

Moreover, the depth and breadth of the foundational literature can be observed in the 59,051 references cited across these publications. Diving deeper into the content of these documents, are found 2559 keywords that have been algorithmically generated as keywords plus, while the 3567 authors identified have proactively designated 3026 specific keywords, which underscores the multifaceted nature of the discourse on the potential of new technologies to drive the circular economy. Furthermore, the international character of this research is highlighted by the fact that 36.4% of the articles boast international co-authorships, reflecting the global resonance of the topic and the cross-border collaborative spirit of the academic community. The steady increase in the number of articles published yearly during the last decade, from 12 articles in 2013 to 341 in 2022 (annual growth: 45.05%), shows that the potential of new technologies in driving the circular economy transitioned from a nascent area of inquiry to a focal point of scholarly discourse.

3. Results and discussions

3.1. Academic literature on the potential of new technologies to drive the circular economy

The sharp growth occurred in recent years is indicative of the growing importance of technological advances and their application to the field of sustainability in contemporary academic research., and suggests a promising future filled with rich insights and groundbreaking research. In 2019, the scholarly activity increased to 60 publications, reflecting a breakpoint in the field under study, and in 2020 soared to 120, a 100% increase from the previous year. This momentum showed no signs of abating, with 2021 registering a remarkable 219 published articles, while the zenith was reached in 2022, with 341 publications, underscoring the upward trend of academic engagement in this domain.

The academic literature exploring the potential of new technologies in driving the circular economy in the last decade is richly textured, being comprised by 484 journals. They reflect the academic interest in the confluence of technology and the circular economy, as well as the interdisciplinary and multifaceted nature of the discourse, having applied different perspectives that offer a holistic understanding of the transformative potential of new technologies in shaping a sustainable future. Regarding to the most prolific journals in this field, at the vanguard are two journals, Sustainability, with 66 articles, which is well known for its interdisciplinary approach, and Journal of Cleaner Production (49), which has a great storied legacy and has been a benchmark in research on sustainable production and consumption.

The third and fourth place correspond to Energies (15), which delves into advanced energy systems and technologies, and Business Strategy and the Environment (14), that offers insights into the strategic implications of environmental considerations in business. Then, per number of published articles are found the multidisciplinary journal Applied Sciences-Basel (12), IEEE Access (12) a hub for electrical and electronic engineering research, and Resources Conservation and Recycling (11), a journal aligned with the principles of the circular economy that emphasizes resource optimization and waste reduction. Finally, with 10 publications, are Environmental Science and Pollution Research, that publishes interdisciplinary research on the development of sustainable environmental solutions and pollution mitigation, Sensors, which covers from the development of novel sensor materials and devices to their applications, and Waste Management, a journal that focuses on the generation, prevention, characterization, monitoring treatment, handling, reuse, and ultimate residual disposition of solid wastes.

Annex 1 provides a chronological account of the academic contributions made by the top ten most prolific journals in the domain of new technologies driving the circular economy in the last decade. Observing the temporal progression, can be discerned a palpable surge in scholarly interest over the years, being a gradual uptick from 2017 onwards. In percentage terms, the collective contributions of these journals account for 23.48% of the total publications in this domain, underscoring their important role in shaping the academic narrative around this domain.

3.2. Most relevant contributions on the potential of new technologies to drive the circular economy

Table 1 provides a comprehensive ranking of distinguished authors based on their academic contributions in the field under study, as well as other classifications based on the number of global and local citations, and the h-index, offering a holistic view of each author's impact. Based on the information displayed, we can observe that Sarkis J. is classified first in all four rankings (12 A.P., 205 L.C., 11 H, 1450 G.C.), while Kouhizadeh M. is ranked fourth per number of A.P. (6), second per L.C. and G.C. (116, 764), and third per H (6). Subsequently, the authors ranked in three out of four classifications are Wang B. (5 A.P., 5 H, 324 G.C.), and Yu Z. (5 A.P., 5 H, 317 G.C.), while other authors are present in two rankings are Kumar A. (9 A.P., 8 H), Agrawal R. (6 A.P., 4 H), Ramakrishna S. (6 A.P., 5 H), Zhu Q.Y. (87 L.C., 335 G.C.), Nandi S. (42 L.C., 313 G.C.), Kazancoglu Y. (39 L.C., 4 H), and Bag S. (34 L.C., 433 G.C.).

Table 2 provides an overview of the most globally cited articles that delve into the potential of new technologies to drive the circular economy which, representing a confluence of rigorous research and impactful insights, have garnered significant attention within the academic community and beyond, since global citations refer to the total number of times a publication has been cited by researchers worldwide. In addition, are displayed the most locally cited articles, that is, the number of times that these articles have been cited within the analyzed database (local citations), providing insights into their influence and relevance within this specialized domain. It is worth highlighting the most global cited article, developed by Kouhizadeh M., and published in 2021 in the International Journal of Production Economics. In the realm of academic research, the number of citations is utilized as an indicator to measure the impact and relevance of publications.

However, when comparing the citation counts of various articles, it is important to also consider other factors that might influence their comparison, such as the age of the publication and the citation practices of different fields, and here is where the concept of normalized global citations comes into play, providing a more accurate reflection of their relative impact and significance, since they refer to the number of citations a publication receives relative to the average number of citations received by similar publications in the same field and time period, while the concept of normalized local citations have the same aim, but limited to the citations contained in a specific field or ecosystem, such as the databased analyzed (Bornmann et al., 2020; Rousseau and Rousseau, 2021; Meitei et al., 2023).

According to these authors, normalized citations are calculated to assess the impact of scholarly publications while considering variations in citation patterns across different academic fields and time periods, and involves two key steps, the first of which is determine the raw citation count of a publication from relevant citation databases, such as WoS, while the second is to normalize the citation count, by dividing it by a benchmark value, typically the average or median number of citations received by similar publications in the same field and published within the same timeframe, to account for these variations.

Therefore, they refer to the adjustment of raw citation counts to ensure a more equitable comparison across various parameters, allowing researchers to mitigate the inherent biases and discrepancies that might arise due to differences in publication age, disciplines, or even journals, e.g., an older article naturally had more time to accumulate citations compared to a more recent publication,

Table 1
Leading authors.

Rank	Authors	A.P.	MLC authors	L.C.
1	Sarkis, J.	12	Sarkis, J.	205
2	Kumar, A.	9	Kouhizadeh, M.	116
3	Agrawal, R.	6	Zhu, Q.Y.	87
4	Kouhizadeh, M.	6	Behdad, S.	49
5	Ramakrishna, S.	6	Nandi, S.	42
6	Rejeb, A.	5	Kazancoglu, Y.	39
7	Singh, R.	5	Zhang, A.	36
8	Wang, B.	5	Bag, S.	34
9	Yu, Z.	5	Kumar, V.	33
10	Chen, Y.	4	Mukhuty, S.	33
Rank	**Authors**	**H**	**MGC authors**	**G.C.**
1	Sarkis, J.	11	Sarkis, J.	1450
2	Kumar, A.	8	Kouhizadeh, M.	764
3	Kouhizadeh, M.	6	Bag, S.	433
4	Ramakrishna, S.	5	Saberi, S.	381
5	Wang, B.	5	Pretorius, J.H.C.	353
6	Yu, Z.	5	Zhu, Q.Y.	335
7	Agrawal, R.	4	Wang, B.	324
8	Gupta, S.	4	Yu, Z.	317
9	Javed, M.F.	4	Nandi, S.	313
10	Kazancoglu, Y.	4	Khan S.A.R.	306

Source: Own elaboration. Note: MLC = Most local cited; A.P. = Articles published; L.C.: Local citations; G.C.: Global citations; H = H-index.

Table 2
Top global cited papers.

Per global citations	GC	GC per Year	Normalized GC
Kouhizadeh M., 2021, Int J Prod Econ	381	127.00	14.10
Esmaeilian B., 2020, Resour Conserv Recy	251	62.75	8.40
Rajput S., 2019, Int J Inform Manage	248	49.60	8.28
Zeng X.L., 2015, Renew Sust Energ Rev	224	24.89	7.30
Zheng T., 2021, Int J Prod Res	216	72.00	8.00
Qureshi M.S., 2020, J Anal Appl Pyrol	215	53.75	7.19
Kouhizadeh M., 2020, Prod Plan Control	212	53.00	7.09
Bag S., 2021, Technol Forecast Soc	203	67.67	7.51
Nandi S., 2021, Sustain Prod Consump	203	67.67	7.51
Klerkx L., 2020, Glob Food Secur-Agr	197	49.25	6.59
Per local citations	**LC**	**LC/GC Ratio**	**NLC**
Kouhizadeh M., 2020, Prod Plan Control	55	0.2594	23.57
Upadhyay A., 2021, J Clean Prod	33	0.1953	17.71
Kouhizadeh M., 2019, Appl Sci-Basel	31	0.3100	17.06
Esmaeilian B., 2020, Resour Conserv Recy	30	0.1195	12.86
Nandi S., 2021, Sustain Prod Consump	27	0.1330	14.49
Bockel A., 2021, Sustain Prod Consump	25	0.3788	13.42
Rajput S., 2019, Int J Inform Manage	24	0.0968	13.21
Kouhizadeh M., 2021, Int J Prod Econ	24	0.0630	12.88
Chidepatil A., 2020, Adm Sci	23	0.3898	9.86
Wang B., 2020, Comput Ind	21	0.2308	9.00

Source: Own elaboration. Note: LC = Local citations; GL = Global citations.

some research fields might have more frequent publication rates and larger researcher communities, leading to higher citation counts.

The combination of local citations, local/global citations ratio, and normalized local citations offers a multi-dimensional understanding of their impact within the field under study, as well as the dynamic interplay of global recognition and local significance. It is worth mentioning the leading article developed by Kouhizadeh M. in 2020, and published in Production Planning and Control, which local relevance is reflected on the 55 local citations reached, a LC/GC ratio of 25.94%, and a normalized local citation score of 23.57.

In connection with the most prolific universities in the field under study, the fact that they are spread across several continents underscores the global collaborative spirit in this domain. Each institution, with its unique strengths and regional insights, enriches the discourse, promising a holistic understanding of the transformative potential of new technologies in the circular economy. De La Salle University, located in Manila, Philippines, is well-known for its commitment to research and innovation, and leads the ranking with 16 articles. This university houses several research centers and institutes dedicated to sustainability, innovation, and technology, which often collaborate with international organizations, industries, and other academic institutions, fostering a multidisciplinary approach and enabling knowledge exchange, joint research projects, and academic programs tailored to address global sustainability challenges.

Regarding to the rest of universities that comprise the ranking, Indian Institute of Technology (12), Islamic Azad University (12), University of Johannesburg (12), National University of Singapore (10), Queensland University of Technology (10), University of Florida (10), University Kebangsaan Malaysia (10), Yonsei University (9), and University of Queensland (9), they are commonly situated in regions with specific sustainability challenges or opportunities, such as unique ecosystems, industrial landscapes, or policy environments (Vaz et al., 2021; Frantzeskaki et al., 2022; Nudurupati et al., 2022; Udeagha & Muchapondwa, 2023; Assamoi and Wang, 2023; Zhao et al., 2023). Therefore, their research used to reflect these localized contexts, providing nuanced understandings that can be invaluable in a global perspective, and have an interdisciplinary approach, generally bringing together experts in technology, sustainability, economics, and social sciences to address the complex challenges of the circular economy (Alam et al., 2022; Huseien and Shah, 2022; Ali et al., 2023; Mukherjee et al., 2023; Parhamfar et al., 2023). They also often form creative partnerships with industry, government, or larger academic institutions, which can result in research that is immediately applicable, with a clear pathway from academic inquiry to real-world implementation.

To enhance the understanding of the most relevant contributors all over the world, the most important countries per number of articles published, as well as the number of citations received withing the domain analyzed, are detailed in Annex 3, thus utilizing two indicators that reflect the quantity and quality of their scientific production.

In this vein, is also emphasized the collaborative and global nature of research in driving the circular economy through new technologies. As can be observed, with regard to the most active countries in generating new knowledge in this domain, China is classified first with 131 articles published, followed by the U.S.A. (71), India (60), Italy (54), the United Kingdom (43), Poland (39), Germany (37), Spain (37), Iran (31), and Australia (27). In connection with the first one, which also is ranked first per number of citations received (2997), the Chinese political system allows for centralized, long-term planning, and the government provides substantial funding and policy support for research and development, particularly in areas that align with national priorities like technology and sustainability, which are implemented through different strategic actions, such as their five-year plans (Hepburn et al., 2021; Stern and Xie, 2023). Moreover, because of its huge industrial capacity, China faces significant challenges related to pollution and resource utilization, making research into the circular economy both an economic and environmental necessity (Chen et al., 2023). For this reason, in the last years, China has been implementing policies that encourage or mandate the adoption of sustainable practices and technologies, thereby stimulating academic interest and research in these areas (Fang, 2023; Guo et al., 2023; Li et al., 2023).

In terms of the most cited, instead of being classified seventh per number of articles published, with 37, Germany ranks second with 2721 citations. This may be due to the German culture, that often emphasizes "Gründlichkeit" (thoroughness), which can drive the production of high-quality research, and the high level of public awareness and support for sustainability and environmental issue, which can influence the kind of research that gets attention and funds (Ali-Toudert et al., 2020; de Wilde, 2021). In connection with the above, Germany has a strong policy framework that supports sustainability and innovation, has strict regulations for environmental protection and waste management, and is well known for its significant investment in research and development, often in collaboration with the European Union, which favors the creation of fertile ground for high-impact research, especially in the field of the circular economy (Lu et al., 2020; Oei et al., 2020; Broska et al., 2022).

Furthermore, its industrial base provides both the need and the resources for cutting-edge research, also having a strong tradition of collaboration between academia and industry, often leading to research that is not only academically rigorous but also practically impactful (Freire and Gonçalves, 2022; Jäger et al., 2022; Prodi et al., 2022; Kosmützky and Krücken, 2023). Therefore, while it may not lead in the sheer volume of publications, the research it produces is often of such high quality that it garners more citations, thereby leading in impact, together with other countries such as China (2997), the U.S.A (1723), the United Kingdom (1581), Italy (1225), India (1034), Iran (826), Finland (752), Australia (567), and Poland (524).

Fig. 2 show the seminal articles on the potential of new technologies to drive the circular economy, and their interconnection, so that the two most relevant co-citation patterns have been identified, which are differentiated by color, while the size of the circles represent the degree of centrality of each research paper within the network. Co-citation analysis is a bibliometric technique designed to scrutinize instances where two distinct articles are conjointly cited within a third scholarly work, typically within a specified database, serving as a robust tool for identifying seminal works that have collectively shaped the intellectual landscape of a given field (Paul and Benito, 2018; Raposo et al., 2018; Batistič & van der Laken, 2019). Therefore, aids in uncovering relationships between articles, providing a more precise understanding of how academic contributions are interconnected and how they collectively contribute to the advancement of knowledge.

3.3. Research fronts developed on the potential of new technologies to drive the circular economy

This section presents the results of the analysis carried out on the main research fronts developed over the last decade on the potential of new technologies to drive the circular economy. Firstly, the most common keywords, showed in Table 3, are identified and discussed, since is one of the most simply and effective ways to gain superficial insights about the subtopics analyzed within a specific field. In this sense, the results show the most relevant areas within the research on circular economy, as well as those technologies that have proven to be most effective in boosting the efficiency of supply chains, processes, and inputs, as well as the reuse of waste, among other aspects or activities related to the circular economy. Therefore, it provides a snapshot of the current state of the field, enabling to identify research gaps, future directions, and the interconnectedness of various subtopics, as well as the complexities and opportunities that define this important area of research.

Among the most common keywords, can be identified some core concepts in the field analyzed, such as circular economy, sustainability, waste management, and recycling. The concept of the circular economy stands as the cornerstone of this research domain (178 occurrences), making evident that transitioning from a linear to a circular economic model is the central focus, which involves not

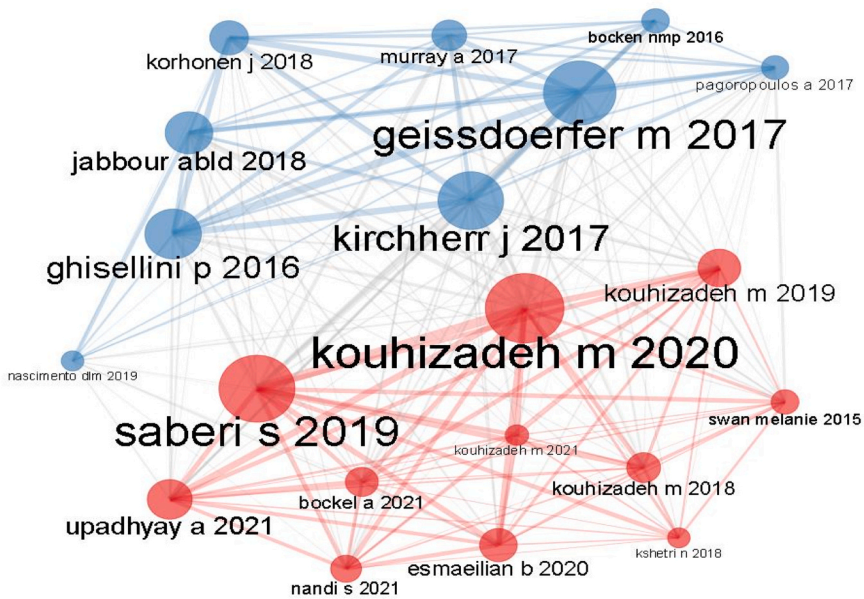

Fig. 2. Co-citation network of papers.

Table 3
Most used keywords.

Rank	Words	Ocur.	Rank	Words	Ocur.
1	Circular Economy	178	11	Deep Learning	20
2	Artificial Intelligence	119	12	Big Data	18
3	Sustainability	89	13	Digitalization	18
4	Blockchain	81	14	Artificial Intelligence (AI)	17
5	Industry 4.0	62	15	IoT	17
6	Waste Management	55	16	Life Cycle Assessment	16
7	Machine Learning	47	17	Smart Cities	16
8	Recycling	31	18	Artificial Neural Network	15
9	Internet Of Things	27	19	Supply Chain	15
10	Blockchain Technology	26	20	Sustainable Development	15

Source: Own elaboration. Note: Occur.: Occurrences.

just recycling but also reusing, refurbishing, and remanufacturing products to extend their lifecycle. Another key concepts that are intrinsically linked to the previous one is sustainability and sustainable development (89, 15), which broaden the scope of the previous one to include, in addition to the efficient use of resources, other social and economic dimensions. The frequent appearance of these terms indicate that the research is not just about technical solutions but also about creating systems that are ecologically viable, economically feasible, and socially equitable.

Regarding to waste management (55), recycling (31), and supply chain (15), these terms are closely related and focus on the practical aspects of implementing a circular economy. Waste management involves a set of activities for the collection, transport, treatment, and disposal of waste, aimed at managing waste in a way that it becomes a resource rather than a burden (Lin et al., 2022; Zan et al., 2022). Recycling, on the other hand, is a specific waste management technique that involves converting waste materials into new products, being one of the key strategies in a circular economy aimed at reducing the consumption of raw materials, thereby reducing energy usage and pollution (Tonini et al., 2022; Pacheco-López et al., 2023). A focus on the supply chain suggests an interest in extending circular principles to logistics and procurement processes. The frequency of these terms suggests that practical, actionable solutions for waste reduction, supply chain efficiency, product traceability, and resource optimization are a significant area of focus.

Other keywords refer to some concepts that can be classified as technological enablers of circular economy, serving as critical instruments that facilitate the realization of core concepts. In this regard, are found keywords such as artificial intelligence (119), machine learning (47), blockchain or blockchain technologies (81, 26), industry 4.0 (62), and IoT or internet of things (27, 17) These technological enablers are not just supplementary tools but rather integral components that can significantly amplify the impact of circular economic models (Lei et al., 2023; Sassanelli et al., 2023; Siakas et al., 2023). Artificial Intelligence and its subset, Machine Learning, emerge as the most frequently cited technological enablers, suggesting that they are considered essential technologies in automating and optimizing various processes within the circular economy, e.g., artificial intelligence algorithms can analyze vast datasets to identify inefficiencies in resource use, thereby enabling more sustainable practices while machine learning, specifically, can adapt and improve over time, offering increasingly effective solutions for waste management, resource allocation, and even predictive maintenance of machinery to extend product lifecycles (Kowsari et al., 2023; Prioux et al., 2023).

Blockchain technology is another key enabler, with its primary strength lying in its ability to ensure transparency and traceability (Frikha et al., 2023; Spychiger et al., 2023). In a circular economy, where the lifecycle of a product involves multiple stakeholders, from manufacturers to consumers and recyclers, blockchain can securely and transparently track each product, enhancing consumer trust and facilitating regulatory compliance, thus making it easier to implement circular practices on a large scale (Meier et al., 2023; Yontar *et al.*, 2023). The internet of things is another significant technological enabler, focusing on the interconnectivity of devices and systems, playing a crucial role in real-time data collection and monitoring, which is essential for effective waste management, energy use optimization, and predictive maintenance (Martikkala et al., 2023; Soori et al., 2023b), while the interconnected sensors can provide actionable insights that can be used to make immediate adjustments, thereby contributing to more sustainable practices (Matin et al., 2023; Bibri et al., 2024).

For its part, the term industry 4.0 refers to the fourth industrial revolution, characterized by the integration of digital technologies like artificial intelligence, internet of things, or blockchain into traditional industries (Chen et al., 2022; Hassoun et al., 2023) which, in the context of a circular economy, signifies the transformative potential of these technologies to revolutionize manufacturing processes, supply chain management, and even consumer engagement, making them more efficient, transparent, and sustainable (Gebhardt et al., 2022; Faisal, 2023). The frequent occurrence of these keywords in the academic literature on the field analyzed underscores their perceived importance in accelerating the transition to a more circular and sustainable economic model, since each of them offers unique capabilities that, when integrated, can provide a robust toolkit for implementing and scaling circular economic practices.

Moreover, there are other concepts that make reference to the possibilities and opportunities that these new technologies represent, such as deep learning (20), artificial neural network (15), big data (18), digitalization (18), life cycle assessment (16), and smart cities (16). Deep learning and the artificial neural network are subfields of machine learning that are increasingly being recognized for their potential to analyze complex and large datasets, and their application for the circular economy purposes could range from advanced waste sorting algorithms to predictive analytics for resource allocation (Attri et al., 2023; Wazirali et al., 2023). The interest in these technologies suggests that researchers are looking for more nuanced and sophisticated artificial intelligence solutions to address the complexities of circular economic systems.

In the context of a circular economy, big data can serve as the analytical engine that powers decision-making at various levels, since has the ability to collect, analyze, and interpret large volumes of data in real-time, allowing for more dynamic and responsive systems, e.g., big data analytics can help in optimizing supply chains by predicting demand, thereby reducing overproduction and waste, as well as assist in resource allocation, ensuring that materials and energy are used as efficiently as possible, so that its importance lies in its ability to provide actionable insights that can drive sustainability at scale (Behl et al., 2023; Liu et al., 2023b; Schöggl et al., 2023). On the other hand, digitalization is the broader process of integrating digital technologies into all aspects of economic activity, so that can facilitate from consumer engagement through apps that encourage recycling, to more complex tasks like automating waste sorting and resource recovery (de Oliveira et al., 2023; Mondal et al., 2023b). Moreover, digital platforms enable peer-to-peer sharing of resources, thereby extending product lifecycles, and reducing waste, thus having the capacity to make circular practices more accessible, efficient, and scalable, so that while the first one can provide the analytical backbone for monitoring and optimizing resource flows in real-time, the second refers to the broader integration of digital technologies into all aspects of the circular economy, pointing to a future where data-driven decision-making becomes the norm rather than the exception (Govindan, 2023; Piscicelli, 2023; Xu et al., 2023).

The importance of the extension of product lifecycles as one of the main objectives of circular economy makes life cycle assessment an essential aspect in research, which is a methodological framework for evaluating the environmental impacts of a product or service throughout its entire lifecycle, from raw material extraction to production, use, and disposal (Reslan et al., 2022; Antwi-Afari et al., 2023), that can provide valuable insights into where waste is generated and where efficiencies can be gained, offering a holistic view that aligns well with the principles of circularity, which also advocate for a lifecycle perspective to minimize waste and maximize resource efficiency (Zhang et al., 2021; Toniolo et al., 2023). This type of assessment has the ability to inform better product design, guide sustainable procurement decisions, and provide transparent information to consumers, among other benefits (Marcon et al., 2022; Ma et al., 2022). Finally, smart cities represent an integrated approach to sustainability, where digital technologies are leveraged to improve urban services, reduce environmental impact, and enhance the quality of life, serving as incubators for testing and implementing new technologies and practices, e.g., sensor networks can monitor waste generation and recycling rates, while smart grids can optimize energy use across different sectors (Dana et al., 2022; Alshamaila et al., 2023; Möslinger et al., 2023). They can act as living labs for innovation, and they can scale successful practices to larger populations (Nguyen et al., 2022; Mora et al., 2023).

After a first approach to identify the main research fronts through the analysis of the most frequently used keywords, we then proceed to perform a co-occurrence analysis of keywords, to reveal how they are interrelated, providing greater clarity in relation to the research fronts developed in the last decade on the potential of new technologies to drive circular economy, the results of which are showed in Fig. 3 and Annex 2. This is a methodological approach aimed at identifying the frequency with which specific keywords

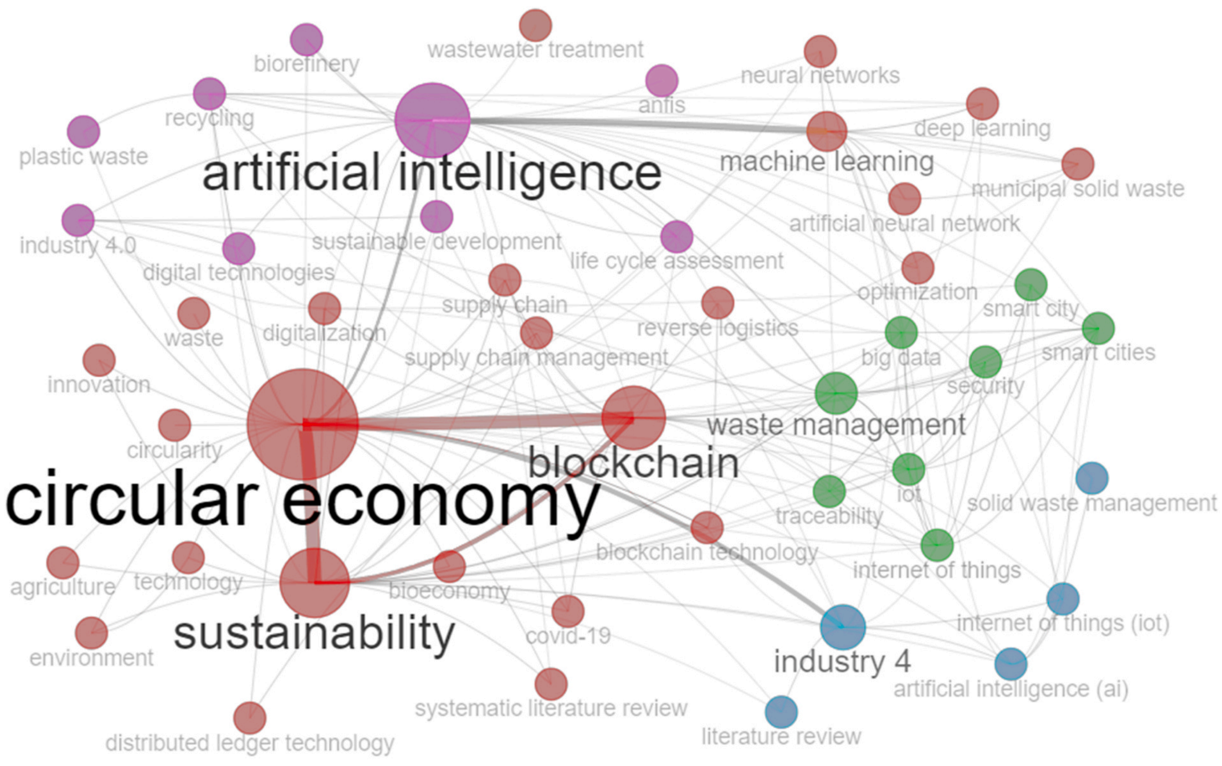

Fig. 3. Co-occurrence network of keywords.

appear together within a corpus of academic literature, unveiling the interconnectedness of various research areas, emerging trends, research gaps and even potential areas for future investigation. This interconnectedness can indicate either a complementary or an interdisciplinary relationship between themes, which is crucial for understanding the complexity and the multi-dimensional nature of a research field.Three metrics have been used to establish the different clusters (betweenness centrality, closeness, and PageRank), since they complement each other in providing a holistic view of the keyword network, revealing the most connected or frequently occurring keywords as well as those that are central to the flow of ideas and bridge different research domains, offering a richer, more interconnected understanding of the research within a field of study (Zhao et al., 2018; Škare et al., 2022; Kumari & Singh, 2023; Beloskar et al., 2024).

According to the previous authors, betweenness centrality, measures the extent to which a particular node serves as a bridge or intermediary within the network, by quantifying how often a node lies on the shortest path between other nodes. A high betweenness centrality score indicates that the node is central in connecting disparate parts of the network, that is, a keyword with high betweenness centrality can be seen as a key theme that links various subtopics or research areas, thereby holding a broker-like position in the intellectual structure of the field. For its part, closeness measures how quickly a node can reach every other node in the network through the network's paths, being calculated as the inverse of the sum of distances from a given node to all other nodes, so that a keyword with high closeness is one that is closely related to many other keywords, suggesting that it is a central and accessible theme within the broader research landscape, so that high closeness can indicate a foundational or core topic that has broad implications across various research areas. Finally, PageRank operates on the premise that important or high-quality nodes are likely to be connected to other important nodes, so that a high PageRank score for a particular keyword suggests that it is frequently co-occurring with other highly occurring keywords, indicating its significance and influence in the research field. Together, these metrics provide a comprehensive understanding of the thematic architecture of a research domain (Donthu et al., 2021; Farooq, 2022; Yaqoub et al., 2023).

The first cluster (red) presents a confluence of technological innovation and sustainability, a fertile intersection where the future of economic development is being reimagined through the lens of environmental conservation. This cluster envision a future where blockchain and artificial intelligence technologies are harnessed to revolutionize supply chain management, making it not just efficient but also transparent and inherently sustainable. These technologies offer endless possibilities, e.g., optimize logistics, inventory management, and the use of scarce inputs, such as energy, water, or mineral resources; increase the efficiency, transparency, and accountability of the waste management process; create transparent and immutable records for sustainability metrics; develop decentralized platforms for sharing resources, which can be used by small firms to participate in the circular economy; provide consumers with verifiable information about the sustainability of their purchases, thereby encouraging more responsible consumption; smart cities; or the simplification of the regulatory compliance (Gupta et al., 2023; Jiang et al., 2023; Khan et al., 2023; Li, 2023; Treiblmaier & Garaus, 2023).

The second cluster (blue) presents a compelling narrative of how technology can be leveraged to address some of the most pressing challenges in modern urban environments., e.g., industry 4.0 technologies, with its emphasis on automation and data exchange, could be the backbone of an advanced waste management system, ensuring that waste materials are not just disposed of but are also recycled or repurposed in the most efficient manner possible, contributing to a circular economy; the internet of things could provide the necessary connectivity, linking various elements like smart bins, recycling centers, and even consumer waste management apps in a cohesive network, and track specific goods in real-time; in this context, big data analytics could predict demand for specific goods, ensuring that there is neither scarcity nor wastage, which is particularly crucial for perishable goods, where waste can have significant environmental impacts; these technologies may also facilitate the rapid manufacturing of essential supplies in response to these predictions (Samuel et al., 2022; Shah et al., 2022; Sharma et al., 2023; Bibri et al., 2024).

The third cluster (green) is focused on the use of some technologies present in the previous clusters, but with security and traceability purposes. Product traceability is becoming increasingly important in a world concerned with ethical consumerism and sustainable supply chains, e.g., these technologies can be utilized to analyze the life cycle of products, from raw materials to end-of-life, and make this information transparent and accessible to consumers, which could revolutionize recycling efforts, as consumers and waste management entities would know exactly what materials are in a product and how to recycle them effectively; advanced encryption algorithms can be developed to secure this data, and machine learning algorithms could monitor these systems in real-time for any security breaches or anomalies; secure and traceable data could provide verifiable proof of a product's environmental impact, which could be crucial for regulatory compliance and influence consumer behavior towards more sustainable choices (Charles et al., 2023; Dedeoglu et al., 2023; Frikha et al., 2023; Matenga and Mpofu, 2023).

The fourth cluster (purple) link the use of new technologies with biorefinery and plastic waste. The concept of biorefinery involves converting biomass into fuels, power, and value-added chemicals (Velvizhi et al., 2022; Kiehbadroudinezhad et al., 2023). In this regard, some possibilities of new technologies may be raised, e.g., explore the role of digital technologies in monitoring, managing, and optimizing biorefinery operations, thus enhancing their efficiency and productivity; drive the feasibility and efficiency of using plastic waste in biorefinery processes; favor the development of secure and transparent systems to trace and manage the lifecycle of plastic products; or allow the design of new products easily recyclable in biorefineries to create a closed-loop system where waste is minimized (Pandey and Singhal, 2022; Baralla et al., 2023; Khanal et al., 2023; Kumar et al., 2023).

The fifth cluster (maroon), besides including machine learning, focus on other new technologies, such as deep learning and artificial neural networks, and link them with challenges as municipal solid waste and optimization. With urban populations booming, efficient waste management becomes crucial (Sathya et al., 2023; Suryawan and Lee, 2023). In this context, machine learning can be employed to predict waste generation patterns, optimize collection routes, and even automate waste sorting processes, while deep learning, with its ability to process vast amounts of unstructured data, can be used to identify and segregate recyclables from waste streams using image recognition, and optimization techniques, when combined with neural networks, can further enhance these processes (Ahmed et al., 2022; Lin et al., 2022; Li and Chen, 2023; Zhao and Li, 2023). Regarding to the sixth cluster (brown), is comprised by the keyword wastewater treatment, which is another domain ripe for innovation, susceptible to be enhanced by using new technologies (Hakak et al., 2020; Aghdam et al., 2023; Mahmod et al., 2023). Finally, the seventh cluster (pink) is composed by the keyword anfis, which is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference system, being designed to function as an adaptive system that adjusts itself to learn from the data it processes (Amadou et al., 2023; Vargas et al., 2023).

Finally, in order to identify the main lines of investigation developed in the last decade on the potential of new technologies to drive the circular economy, the abstracts of the 890 articles that comprise the database analyzed have been revised. As a result, although we could establish an endless number of topics, the following five major research trends have been detected, which are displayed in Table 4 and subsequently explained.

3.3.1. Community and technology integration in the circular economy

The convergence of community dynamics and technological advances constitutes a central axis in the discourse on the circular economy (Liu et al., 2017; Rani et al., 2021). This trend stresses the symbiotic relationship between social structures and technological innovations, emphasizing the role of contractual social utilitarianism in the adoption and implementation of new technologies, thereby emphasizing mutual agreement and collective benefit (Irwansyah, 2020; Van Fan et al., 2020; Branca et al., 2021), representing, in the context of the circular economy, the idea that communities come together, driven by shared interest and mutual agreement, to adopt technologies that promise collective utility and sustainable benefits (Lindkvist Haziri et al., 2019; Hernández-Chover et al., 2022). Inasmuch as the success of new technologies in driving a circular economy depends on both their technical capabilities and their acceptance, adoption and integration by society, this line of research delves into the analysis of the linkage between new technologies and society, as a starting point for harnessing their full potential in favor of achieving circular economy goals, and the challenges and opportunities associated (Raepsaet et al., 2021; Govindan, 2022; Hrouga et al., 2022; Martins et al., 2022). In this sense, a commonly accepted proposition seems to be that for technologies to be truly transformative, they must resonate with the values, needs and aspirations of the communities they are intended to serve (Matviychuk-Soskina et al., 2019; Schneider, 2022; Rejeb et al., 2022).

3.3.2. Sustainable business models and technological synergies

In the context of the circular economy, the confluence of sustainable business models and technological synergies emerges as a prominent research trend, signaling a transformative shift in the way businesses operate and innovate in the 21st century (Díaz-Díaz et al., 2017; Belova, 2021). The essence of this trend lies in the recognition that mere technological advances, while crucial, are insufficient to drive the circular economy; rather, these advances must be properly integrated into business models that prioritize sustainability, resource efficiency and long-term value creation, which ensures the viability and scalability of technological solutions, and aligns them with broader economic, social and environmental objectives (Ramakrishna et al., 2020; Saura et al., 2022). A key aspect of this line of research is the exploration of how companies can leverage new technologies to create value in an economically profitable and environmentally sustainable way because, while they offer companies unprecedented opportunities to optimize resource use, improve process efficiency and reduce waste, their true potential is realized when they are integrated into business models that advocate circularity, reuse, and regeneration (Turner et al., 2019; Esmaeilian et al., 2020; Erol et al., 2021; Chauhan et al., 2022). Moreover, the research underscores the challenges that companies face in this transition, as well as the importance of creating an enabling environment for collaboration, in which business, government, academia and civil society work together to create solutions, share best practices, and drive collective action (Lähdeaho and Hilmola, 2020; Ratner et al., 2021; Voulgaridis et al., 2022).

Table 4
Main research trends identified.

Research front	Research papers
Community and technology integration in the circular economy	(Chandran *et al.*, 2014; Ricciardi *et al.*, 2014; Ren *et al.*, 2015;Liu et al., 2017; Wang *et al.*, 2018;Lindkvist Haziri et al., 2019;Matviychuk-Soskina et al., 2019; Irwansyah *et al.*, 2020;Van Fan et al., 2020;Branca et al., 2021; Raepsaet et al., 2021;Rani et al., 2021;Govindan, 2022;Hernández-Chover et al., 2022;Hrouga et al., 2022; Martins et al., 2022;Rejeb et al., 2022;Schneider, 2022; Soulé *et al.*, 2022).
Sustainable business models and technological synergies	(Díaz-Díaz et al., 2017; Kuo & Smith, 2018; Wells & Nieuwenhuis, 2018; Chojnacka *et al.*, 2019;Turner et al., 2019; Cioffi *et al.*, 2020;Esmaeilian et al., 2020;Lähdeaho and Hilmola, 2020;Ramakrishna et al., 2020;Belova, 2021;Erol et al., 2021; Gkountani & Tsoulfas, 2021;Ratner et al., 2021;Chauhan et al., 2022;Saura et al., 2022; Véliz *et al.*, 2022;Voulgaridis et al., 2022).
Ethical implications of technological advances	(La Fors et al., 2019;Natal'ya, 2021;Yara et al., 2021;Upadhyay et al., 2021;Iacono, 2022;Lehtokunnas et al., 2022;Roberts et al., 2022).
Waste management and sustainability	(Managi *et al.*, 2014; Escorihuela, 2015;Cesetti and Nicolosi, 2016;da Silva et al., 2016;Popescu et al., 2016; Holtzer *et al.*, 2017; Mbareche *et al.*, 2018; Al-Alawi *et al.*, 2019; Pattnaik & Dangayach, 2019;Schindler and Demaria, 2020; Krzywnicka *et al.*, 2020; Owusu-Sekyere *et al.*, 2021;Puertas and Marti, 2021;Sreenath et al., 2021;S. Gupta et al., 2022; H. Gupta et al., 2022;Razip et al., 2022;Seay and Ternes, 2022; Wang *et al.*, 2022;.).
Bioeconomy and circular economy	(Satpute et al., 2017; Laibach et al., 2019; Bröring *et al.*, 2020;Klerkx and Rose, 2020; Matheri *et al.*, 2021; Tsapekos et al., 2021; Aggestam & Giurca, 2022;Ajeng et al., 2022; Clauser *et al.*, 2022;D'Amico et al., 2022; Giese, 2022;Goswami et al., 2022; Holt *et al.*, 2022;Kacprzak and Sobik-Szołtysek, 2022; Lavelli & Beccalli, 2022; Matheri et al., 2022;Pyka et al., 2022;Tsui et al., 2022).

Source: Own elaboration.

3.3.3. Ethical implications of technological advances

While technological innovations are generally hailed as harbingers of sustainable transformation, this line of research develops a parallel narrative that critically examines the ethical implications of these advances, looking beyond mere economic and environmental considerations by exploring the moral, social, and philosophical dimensions of the integration of new technologies into circular systems (La Fors et al., 2019; Lehtokunnas et al., 2022; Roberts et al., 2022). This concern ranges from personal data privacy and surveillance to broader questions of technological determinism, equity, and social justice, being underscored issues such as the commodification of personal data, surveillance capitalism, and the risk of reinforcing existing power dynamics in which large corporations have disproportionate control over data and its monetization, as well as the social implications of technological integration, i.e., ensuring that the benefits of technological advances are distributed equitably and do not inadvertently perpetuate or widen social divisions, as well as the philosophical underpinnings of technological determinism in the context of the circular economy, raising a number of introspective questions about the very nature of technological neutrality and the responsibility of technological innovators in ensuring that ethical considerations are integrated into their design and deployment (Natal'ya, 2021; Upadhyay et al., 2021; Yara et al., 2021; Iacono, 2022; Lehtokunnas et al., 2022).

3.3.4. Waste management and sustainability

At the core of this discourse is the recognition that waste is not a mere by-product of consumption, but a usable resource (Schindler and Demaria, 2020). The traditional linear model of production and consumption is currently at the center of criticism, in the face of the novel paradigm of the circular economy, focused on the use of waste and the elimination of waste products, which rethinks the very definitions of waste and value (Razip et al., 2022; Seay and Ternes, 2022). Technological advances are currently revolutionizing waste management processes, and this line of research highlights that the integration of waste management and sustainability requires the confluence of technological innovation with social engagement, such that community-driven waste reduction initiatives, grassroots movements advocating sustainable consumption, and educational campaigns play a crucial role in forming a collective consciousness that values sustainability, which is a symbiotic relationship in which social awareness determines technological deployment and vice versa (Cesetti and Nicolosi, 2016; da Silva et al., 2016; Gupta et al., 2022). Furthermore, this line delves into the political dimension of waste management, as effective waste management requires sound policy frameworks that incentivize sustainable practices, promote research and development of waste management technologies, and foster public-private partnerships, so that the role of regulatory agencies in setting standards, ensuring compliance, and facilitating knowledge sharing is paramount (Popescu et al., 2016; Puertas and Marti, 2021; Sreenath et al., 2021).

3.3.5. Bioeconomy and circular economy

This research trend, while grounded in the principles of resource efficiency and environmental stewardship, also resonates with the broader aspirations of social welfare and economic resilience (Matheri et al., 2022; Pyka et al., 2022). The bioeconomy, in essence, is the utilization of biological resources, processes and principles to drive economic activities, which is why it focuses primarily on sectors such as agriculture, forestry, fisheries and biotechnology, with the aim of producing goods and services with reduced environmental impact, a concept that is closely linked to that of the circular economy (Satpute et al., 2017; Klerkx and Rose, 2020; Ajeng et al., 2022). In this sense, the convergence of the bioeconomy and the circular economy can generate powerful synergies, because when biological resources are managed sustainably, they provide renewable inputs for industries, reducing our dependence on finite and non-renewable resources, while innovations in biotechnology can lead to the development of bio-based chemicals and fuels,

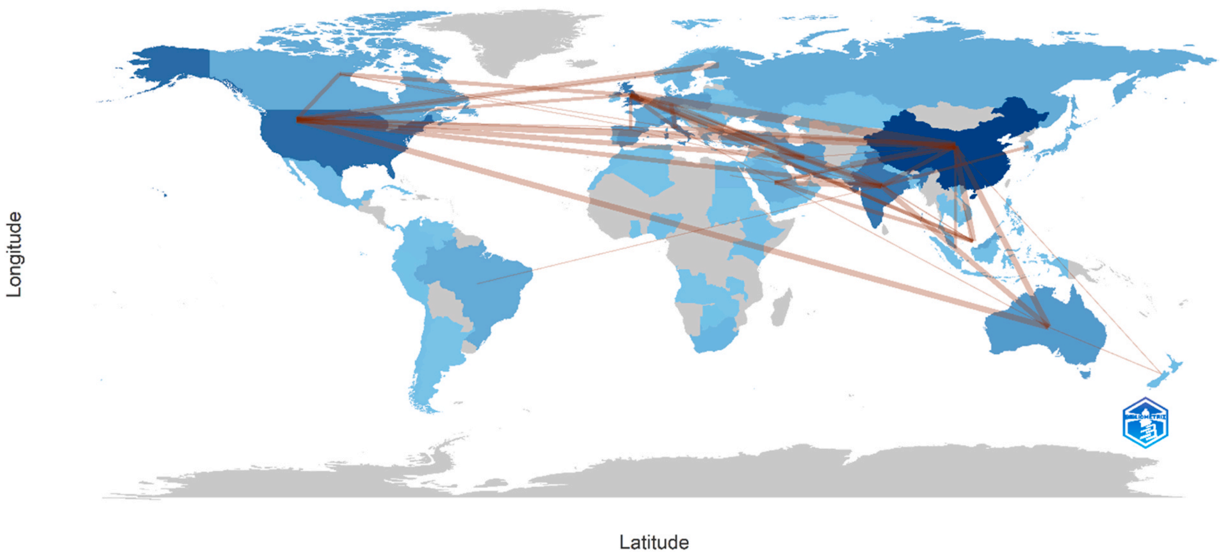

Fig. 4. Collaboration world map.

offering sustainable alternatives to their petrochemical counterparts (Laibach et al., 2019; Tsapekos et al., 2021; Giese, 2022; Goswami et al., 2022). However, these synergies go beyond mere resource substitution towards the creation of value chains that are regenerative by design, being also underscored the socio-economic dimensions of this convergence (D'Amico et al., 2022; Kacprzak and Sobik-Szołtysek, 2022; Lavelli & Beccalli, 2022).

Finally, Fig. 4 provide a panoramic snapshot of the countries collaborating the most in research on the potential of new technologies to drive circular economy, reflecting an interconnected, collaborative, and united global research community making joint efforts to create a more sustainable, inclusive, and technologically advanced future. China leads the ranking having established, within the period analyzed and the field under study, different partnerships with countries such as the United Kingdom (18), the U.S.A. (12), Pakistan (11), Malaysia (10), Australia (9), India (7), Italy (7), Singapore (5), Iran (4), New Zealand (4), and Saudi Arabia (4), among others. It is also worth highlighting the role of other countries, such as India, the United Kingdom, and the United States. These collaborations, bridging diverse cultures and geographies, are a source of progress and signal a collective determination to forge a technologically advanced and ecologically sustainable future.

The confluence of technology and sustainability implies a profound shift in our collective consciousness. The global commitment to harness new technologies to drive the development of the circular economy reflects the aspiration to redesign our world from the current linear model of production and consumption to a harmonious cycle of renewal, reuse, and sustainability. This transition, marked by both the challenges and opportunities it poses for the future of humanity, finds in new technologies the necessary tools to sculpt a technologically advanced and ecologically sustainable future.

The analysis carried out in this research paper on the potential of new technologies to drive the circular economy has been enlightening, revealing the immense possibilities as well as the inherent challenges. This is an incipient field of study in which everything remains to be done, so academics, entrepreneurs, and policy makers must collaborate in the development of new solutions to harness the full potential of new technologies to harness the waste generated by the current system of production and consumption, reducing the waste that floods our seas and territories.

The international research collaboration context reveals a collective effort to harmonize technological advances with ecological imperatives, which is fraught with challenges that require a thorough understanding of the situation and the application of interdisciplinary approaches to design new options for the utilization of waste generated by the current production and consumption system. The steady increase in academia's attention to this field of study since 2018, together with the high degree of international research cooperation, reflect a shared vision, as well as a mutual recognition of challenges that transcend borders, and a commitment to the development of technologically advanced solutions.

In this sense, the new research trends identified shed light on the different perspectives covered by researchers in the last decade and especially in the last three to four years, from the ethical dilemmas posed by artificial intelligence to the pragmatic challenges of applying the latest technologies in waste management, reflect the multidisciplinary nature of this discourse. In addition, the research places particular emphasis on traceability, highlighting the need for increased transparency and accountability of supply chains, while the exploration of bioeconomy models seems to offer hope for the sustainable exploitation of resources and waste, so that some authors, such as Rusch *et al.* (2021), emphasize the role of digital technologies like internet of things, big data, artificial intelligence, and blockchain as enablers for a more sustainable and circular economy, particularly in sustainable product management, while others, such as Rejeb et al. (2021) analyze the digitalization in food supply chains, underscoring the role of technology in enhancing the resilience and efficiency of these systems. However, the path is not without challenges, as the effective integration of these advanced technologies into our social systems requires not only technical prowess, but also ethical and philosophical introspection.

According to Rejeb and Appolloni (2022), new technologies linked to industry 4.0 can accelerate the shift to circular economy, creating a more sustainable and equitable context for businesses and society. Therefore, the implementation of emerging technologies to achieve the goals of the circular economy offers a wide range of possibilities that can redefine the parameters of sustainable business practices, being resource efficiency at the forefront of this transition, with artificial intelligence and machine learning optimizing resource utilization and reducing waste and improving product longevity through predictive analytics, which also extends into the field of supply chain management, where the advent of blockchain technology introduces unprecedented levels of transparency and traceability, facilitating a more streamlined and accountable flow of materials from inception to end-of-life, e.g., the study of Wang and Yu (2023) discuss about the integration of artificial intelligence and blockchain in supply chain management, highlighting the efficiency and security these technologies bring to the system.

Furthermore, as the life cycle management of products is restructured, technologies play a key role in their transformation for disassembly and subsequent reuse, creating a dynamic market for second-hand materials, and constituting the flood of data collected throughout the life cycle of products an information bank, which, thanks to big data analysis, enables companies to make informed decisions in line with the principle of circularity (Knoth et al., 2022; Huang et al., 2023; Júnior et al., 2023). In connection with the above, the digital era generates innovative business models that allow the optimization of the production process, greater engagement and control through the value chain, and the reduction of the firms' environmental impact. Dana et al. (2022), determined that the development and exploitation of digital technologies represents an opportunity to develop more sustainable and innovative business models which, according to Kamalaldin et al. (2020), is a key source of future competitiveness for enterprises.

Moreover, the circular economy is fertile ground for new sources of income and employment prospects, especially in the burgeoning green sectors, in which digital networks become the channels to intensify collaboration, bringing together stakeholders from all sectors in a common mission to reduce waste and promote circular methodologies. In this respect, Nurgaliev and Nurgalieva (2021) underscore the need for personnel management and skill development in a smart production environment Interactive technologies and platforms can engage consumers more directly in circular practices, encouraging sustainable consumption and facilitating the return, recycling, or refurbishing of products, so that, as we can see, the opportunities that technology infuses in the circular economy are not merely incremental but fundamental to building an economy that thrives on sustainability, resilience and continuous innovation (Behl et al., 2023; Hamidu et al., 2023; Roy et al., 2023).

Nevertheless, these opportunities also erect as complex challenges to be addressed when incorporating the emerging technologies into the circular economy (Mendoza et al., 2022; Marsh et al., 2022). Integrating these technologies into production processes requires a complex combination of innovation and adaptation of established methods, the quest for transparency in the supply chain, that involves establishing data protocols that ensure privacy and security, leveraging blockchain and big data capabilities, which is complex and imperative, and the need for employees to develop the necessary skills to manage new technologies, and therefore specific skills development training is urgently required (Centobelli et al., 2022; Takacs et al., 2022; Saccani et al., 2023).

Furthermore, scaling technologies such as additive manufacturing presents considerable challenges, despite their potential to minimize waste and contribute to sustainability (Praveena et al., 2022; Al Rashid and Koç, 2023; Valera et al., 2023), while the broad application of Industry 4.0 technologies and their full alignment with circular economy goals are not yet fully understood, which is a major barrier to their effective deployment (Kamble and Gunasekaran, 2023; Karmaker et al., 2023). In this vein, Dulaimi et al. (2022) underscore the role of digital twins in fostering sustainable smart energy cities, showcasing the potential of these technologies in energy management, while J. Han et al. (2023); H. Han et al. (2023) further emphasize the importance of green technology innovation in manufacturing firms from an ESG perspective, highlighting the need for environmental impact assessment and management in product life cycles. Moreover, the transition faces a skills gap, as the workforce lacks the necessary skills to manage new technologies and therefore specific skills development training is urgently needed, which is added to the basic digital infrastructure needed to support circular economy activities, that represents a major investment challenge, especially for smaller companies (Tavares et al., 2023; Upadhyay et al., 2023).

However, ensuring that the digitalized ecosystem of the circular economy does not become controlled by a single, dominant player is a significant challenge that requires the development of shared digital platforms which are accessible and beneficial to all stakeholders (Carrasco-Farré et al., 2022; Battisti et al., 2022; Safadi and Watson, 2023). In addition, besides the economic barriers to entry for new technologies, the regulatory frameworks may not yet be adapted to support or incentivize their development and implementation, requiring thoughtful policy reform and economic incentives, and neither the consumers, since for their successful implementation it is necessary a shift in consumer behavior and perceptions towards more sustainable practices such as reuse and recycling (Baiano, 2022; S. Gupta et al., 2022; H. Gupta et al., 2022; Soni et al., 2022; Cho et al., 2023; Novak and Mohammadian, 2023).

Therefore, the potential of new technologies, such as blockchain or artificial intelligence, is enormous, but so are the responsibilities they entail, which highlights the importance of community consensus in the adoption and application of new technologies, making necessary a harmonious integration of technological advances with social values, and ensuring that the adoption of technology is not only technically sound, but also ethically and socially acceptable.

4. Practical applications and future research prospects

New technologies provide a wide range of possibilities to address key aspects of resource management, waste reduction, and consumer engagement, among others, all of which are essential for the transition towards a more sustainable and circular economy. Artificial intelligence and machine learning are revolutionizing waste management by enhancing sorting processes and extending product lifecycles through predictive maintenance, streamlining recycling, and optimizing resource use, contributing significantly to environmental conservation, e.g., artificial intelligence is being leveraged by several cities like San Francisco and Seoul to optimize waste collection routes, reducing fuel consumption and emissions, while some firms, such as Siemens use it for predictive maintenance in its factories, significantly reducing downtime and resource wastage.

In connection with the above, blockchain technology emerges as a game-changer in supply chain management by offering unparalleled transparency and traceability, thus fostering more responsible and sustainable production and consumption patterns, enabling products to be traced from origin to end-user, ensuring responsible sourcing and reducing the incidence of counterfeit goods, e.g., the responsible sourcing blockchain network is a collaboration among multiple companies to trace the origin of metals used in consumer products. In this vein, the internet of things also enables efficient tracking of products throughout their lifecycle and provides valuable data that can be used to improve product design for durability and recyclability, e.g., Philips' pay-per-lux model is an example where internet of things is used to monitor the usage of lighting solutions, promoting a usage-based economy over ownership.

Moreover, the analysis of vast amounts of data through big data analytics allows to optimize the resource flows and understand consumer behavior, among other applications, e.g., precision agriculture uses big data to optimize water and fertilizer use, reducing waste and environmental impact, while energy companies use this technology to improve the efficiency of renewable energy systems. Additive manufacturing introduces a new dimension to production, emphasizing local, on-demand manufacturing that minimizes waste and transportation emissions, promoting efficient material usage and reducing the environmental footprint of production processes, e.g., Adidas uses 3D printing to create shoes with less material waste, and Local Motors is using it to manufacture parts for vehicles, reducing inventory and waste. Finally, digital platforms facilitate the recycling and refurbishing of products and serve as collaboration platforms, bringing together various sectors to innovate and share best practices in sustainability, engaging consumers and stakeholders in circular economy practices, e.g., platforms like the Ellen MacArthur Foundation's Circular Economy 100 network facilitate collaboration and sharing of best practices in sustainability, while apps like OLIO connect neighbors to share surplus food, and platforms like Loop are reimagining packaging by offering reusable containers for everyday products.

However, a future in which new technologies drive the circular economy requires the support of governmental agencies, which can foster their adoption through incentives such as subsidies, tax breaks, and funding for research and development, thus encouraging economic agents and research institutions to invest in and explore new roles of these technologies to drive circular economy. Moreover, educational programs and skill development initiatives focused on providing training in emerging technologies and circular economy principles should be a priority for governments, since there is a need for trained human capital that can meet the business demand for personnel specialized in the design and implementation of innovative solutions based on new technologies. Nevertheless, one of the greatest challenges facing governments is the pressing need for regulations to ensure ethical practices in the use of new technologies, particularly data privacy and security, since they often rely on large datasets to function optimally, so that there is a risk of personal data being misused or mishandled.

Furthermore, as we move towards a more technology-driven circular economy, there is a risk of exacerbating the digital divide, both in terms of access to technology and in the ability to effectively use and benefit from it, especially in less developed regions, being also a broader social implication regarding consumer behavior and societal norms, because this transition is not just technological but cultural, requiring a shift in consumer attitudes and behaviors towards sustainability. Future policies and regulations must therefore ensure that data are used responsibly and ethically, and with respect for privacy and individual rights, which is vital for building public confidence these technologies, as well as for their in widespread acceptance and use. In addition, governments must design and implement strategies to ensure equitable access to these technologies, which can involve investment in digital infrastructure in underserved areas, education, and training programs to build digital literacy, as well as explore how technology can be used both as a tool for efficiency, and as a means to educate and encourage sustainable practices among consumers and businesses alike.

Regarding possible future lines of research, studies focused on the detailed analysis of each of the research fronts identified in this work could be developed. In addition, it would be interesting to study the specific potential of each of the technologies identified to boost the circular economy, as well as their possible practical applications in different fields, and the combination of different technologies to develop innovative green solutions, e.g., the development of new and more sustainable materials through artificial intelligence, blockchain based systems where consumers earn digital tokens for recycling products, sensors for tracking food waste and order replacements, platforms based on artificial intelligence to match excess resources in one industry with needs in another, mobile applications to gamify sustainable living, advanced predictive analytics that forecast supply and demand cycles in the economy to allow businesses to adjust production in real-time, reducing overproduction and waste, etc.

However, this potential is not without challenges, which must be addressed by researchers in the near future, e.g., guarantee data privacy, reduce the large amount of energy consumed by blockchain technologies, ensure the adaptability and reliability of these technologies across different industries and environmental conditions, make viable the implementation of new technologies by small firms, develop a standardized regulatory framework and guidelines to ensure ethical practice, and avoid inefficiencies, develop new educational systems to train the current and future workforce for the transition towards a technology-driven circular economy, make all these technologies work in perfect harmony to optimize the use of resources and minimize waste, and avoid the risk that the benefits of technology-driven circular economy initiatives are unevenly distributed, favoring developed regions over developing ones, among others. Therefore, while the potential of new technologies to drive the circular economy is immense, addressing these challenges through innovative solutions, collaborative efforts, and supportive policies is essential for realizing this potential effectively and sustainably.

5. Conclusions

We are currently on the cusp of a technological revolution, making it crucial to address this potential with an innovative approach, and ensure that technological advances are aligned with ethical, social, and environmental imperatives. Through the analysis of the main research trends, several research gaps have been identified around the development of employees' technological capabilities, the feasibility of the massive implementation of new technologies in small firms, as well as in the less developed regions, the reduction of their energy consumption, and the adaptation of regulatory frameworks, which represent understudied topics with high potential as the subject of further research. With regard to the limitations, although our dataset is comprehensive, we used the Web of Science database which, although highly regarded and recognized worldwide for the large quantity and quality of archives it holds, may not reflect the totality of the global scholarly discourse on the subject.

CRediT authorship contribution statement

Sánchez-García Eduardo: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manresa-Marhuenda Encarnación:** Writing – review & editing, Validation, Software, Data curation. **Marco-Lajara Bartolomé :** Writing – review & editing, Visualization, Validation, Software, Resources. **Martínez-Falcó Javier:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2023.103509.

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