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Cloud computing as an enabler to a circular economy: a systematic scoping and bibliometric review

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ABSTRACT

Cloud Computing enables the creation of differentiated business models for companies, resulting in lower costs, increased profits through a pay-per-usage model, and addressing environmental issues. In this context, the Circular Economy model could be applied to ensure a commitment to solving environmental issues through Cloud Computing business models, integrating Cloud Computing and Circular Economy methodologies. This study presents a scoping review and bibliometric analysis of the literature on the role of cloud computing (CC) in fostering circular economy (CE) strategies. A total of 33 peer-reviewed articles published between 2008 and 2023 were analyzed to map research trends, identify thematic focuses, and highlight potential gaps. Most research endeavors concentrate on the "Optimize" and "Exchange" actions within the ReSOLVE framework. A geographical bias in publications was observed, with a disproportionate number of publications originating from the Global North, except for India. The findings indicate the presence of opportunities for the advancement of CC initiatives that incorporate CE approaches, encompassing interdisciplinary and transdisciplinary methodologies, with the objective of achieving a robust CE.

KEYWORDS: Cloud Computing. Circular Economy. Consonances.

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INTRODUCTION

Consumption is one of the most pressing issues contributing to environmental degradation (Jorgenson, 2014). The linear way of consuming products, i.e., "take, make, dispose," is prevalent and includes the consumption of electronic products, such as computers or cell phones, which increases damage to environmental resources due to their short life spans (World Economic Forum, 2019). Furthermore, there is no established system for collecting or recycling electronic waste (Bhutta *et al.*, 2011; MacAuley*; Palmer; Shieh*, 2003). It is estimated that 38% of the worldwide electronic waste comes from personal electronic materials (World Economic Forum, 2019).

Circular Economy (CE) aims to reduce the environmental impacts caused by the current linear consumption. On the one hand, linearity in consumption produces a great amount of waste and constantly retrieves new resources from the environment. On the other hand, CE is conceptualized as a regenerative economy where the concept of waste is substituted with restoration and the economic growth concept deviates from the understanding of the extraction of new environmental resources (Nascimento *et al.*, 2018; Okorie *et al.*, 2018).

Although CE is presented as a well-established and relevant theory aimed at sustainable development from a practical perspective (Ghisellini; Cialani; Ulgiati, 2016; Kircherr; Heike; Hekkert, 2017), there are still authors who claim that CE lacks practical actions and tends to be more ideological than political and practical (Corvellec, Stowell; Johansson, 2022). Ghisellini *et al.* (2016), highlighted some early stages of CE development, primarily regarding waste management. Kircherr *et al.* (2017), propose a pathway towards economic equity and sustainable development, while in a revisited study, the authors emphasized that CE requires action from stakeholders and society (Kircherr *et al.*, 2023), a vision that was not previously consolidated. It becomes evident that CE needs concrete grounding to be considered effective and to be implemented successfully. One potential area to enable CE is related to Cloud Computing (CC).

CC is based on a service-oriented perspective on computing, where users may request from a company a specific amount of space, an application, etc. (Qian *et al.*, 2009). By doing so, CC can reduce infrastructure costs for the user, guaranteeing a better relationship with the product by extending its product cycle, reducing electronic waste, minimizing energy consumption, and lowering carbon emissions (World Economic Forum; Ellen MacArthur Foundation 2016). In this context, CC may be an efficient tool to promote an environmental-friendly services where CE principles can be integrated into technology services.

Based on the context presented, the aim of this study is to evaluate CC tools and determine if it is feasible to integrate the advantages associated with this business model with the principles of CE. To achieve this, a ReSOLVE framework will be applied to establish metrics for CE goals. The main contribution of this study is in the evaluation through a CE paradigm and the main literature contributions related to the theme.

Besides this brief introduction, the paper is divided into five additional sections as follows: Theoretical framework comprising an overview of the history of Cloud Computing and Circular Economy, Methodology, Results, Discussion, Conclusions, and References.

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LITERATURE REVIEW

CIRCULAR ECONOMY AND CLOUD COMPUTING

The increase in internet usage has put pressure on existing storage systems, ranging from documents to applications (Qian *et al.*, 2009). As data generation continues to surge, traditional storage infrastructures struggle to keep pace with the growing demands. "Cloud computing is a kind of computing technique where Information Technology (IT) services are provided by massive low-cost computing units connected by IP networks" (Qian *et al.*, 2009).

By the use and development of virtualization into the architecture of the cloud, it becomes possible to transform 10,000 physical computers into 100,000 computers of equivalent capacity. In this sense, each physical computer can support 10 virtual machines (Ali; Meghanathan, 2011). A virtual machine operates with virtualized server resources, memory, input/output devices, and network connectivity. Thus, it is possible to expand the use and role of CC in solving problems.

CE early concepts dates back from 1989, originating from Pearce and Turner's book, where they proposed a material balance model based on economic and environmental assumptions. From this model, three economic functions were derived: a resource supplier, waste assimilator, and direct source of utility functions (Pearce; Turner, 1989, p. 41). This approach can be related to any profitable system, including CC.

The concept gained popularity due to the efforts of Ellen MacArthur Foundation since 2010, an NGO committed to CE expansion (Ghisellini *et al.*, 2016; Ellen MacArthur Foundation 2013). From an extensive literature review Kirchherr *et al.* (2017), established a concept for CE defined as a regenerative economic system which replace coping with mostly reducing materials throughout supply chain but also with recycling and reusing, to replace "end of life" concept and acquire sustainable development. A revisited study of the concepts of CE included technology as an enabler to CE reflecting on the importance of CC in the scenario (Kircherr *et al.*, 2023).

It is possible to achieve sustainable development at the social level by reducing information inequalities and providing low-cost accessibility, at the economic level by decreasing company and user costs in infrastructure, and at the environmental level by scaling down electronic waste. Godbole and Lamb (2018) highlighted the acute demand for CC services, particularly in sectors such as healthcare for electronic medical records, banking for transactions, and the utilization of the internet for communication and public information dissemination.

There are still few studies analyzing CC environment based on a CE approach. Antikainen *et al.* (2018) and Okorie *et al.* (2018) infer about the relationships between digitalization and CE development. Okorie *et al.* (2018) conducted a systematic literature review (n = 174) of peer-reviewed articles between 2000 and early 2018 obtained from Scopus. The authors mainly focused the research related to Industry 4.0 topics and digital intelligence. From their analysis, it was observed there are still specific research agendas regarding CE, such as the categorization of Industry 4.0 technologies to contribute substantially to CE and the opportunities

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that such technologies include, as well as the clear definition of a CE within the context of digital intelligence and Industry 4.0.

Antikainen *et al.* (2018) analyzed surveys applied during the workshop at the event "From waste to Valuable" held in Tampere, Finland. There were 52 respondents who answered two sets of open questions regarding the opportunities and challenges in respect to CE and digitalization. From the analysis, the authors concluded that digitalization enables the reduction of costs, saves resources, and generates trustable data. Furthermore, it facilitated the development of new business models, while emphasizing the need of collaboration with stakeholders and clients. A report from Ellen MacArthur Foundation (2023) also highlights the creation of new business models and the opportunity to work with new labor environments and relations.

From both Antikainen *et al.* (2018) and Okorie *et al.* (2018) was possible to infer about the research gap that still exists regarding CE and CC, as both papers do not directly analyze CC itself. Apart from the lack of studies due to the early development of CE and CC technologies, especially in an integrated context, there is also some authors stating that there is a gap in operational data-driven and solutions from technology (Tseng *et al.*, 2018).

Demestichas and Daskalakis (2020) conducted a literature review on information and communication technology, including CC, Internet of Things, virtual and augmented reality, among others, to investigate their potential in achieving CE goals. Among these technologies, the authors specify that most papers focus on the "reduce" aspect of CE. Furthermore, the authors pointed out the main struggle to the diffusion of CE is related to the lack of technology expertise.

Other studies have frequently analyzed sustainable development and the use of technologies within a broader context. Pham *et al.* (2019), Rosa *et al.* (2019), and Nara *et al.* (2021) have examined the integration of Industry 4.0 with CE. Da Silva and Sehnem (2022) have highlighted various interfaces between Industry 4.0 and CE, including smart factories, natural language processing, advanced manufacturing, automation, deep learning, and others. Cheah *et al.* (2022) have also contributed to this discourse.

All these articles have been based on literature reviews and discussions of aspects related to advancements in CE. For instance, exploring how digital technologies enable a CE of Products (Han *et al.*, 2023), as discussed by Pandey *et al.* (2023) and Kurniawan *et al.* (2023). Additionally, Srivastav *et al.* (2023) have pointed out that electronic waste could be substantially minimized through the adoption of CC infrastructure, including machine intelligence techniques and the use of autonomous tools. Electronic waste presents a significant challenge to sustainable development due to its corrosive or toxic components, rendering the use of other disposal methods impractical. From this perspective, it can be inferred that CC plays a crucial role in the diffusion of CE, aiming for sustainable development worldwide.

METHODOLOGY

The methodology will be divided into three major steps as follows: (i) Conducting a systematic review about the integration of CC and CE; (ii) Conducting a bibliometric review using the collected data; and (iii) Implementing a ReSOLVE framework to analyze the literature data gathered. Each step will be explained sequentially. Scoping reviews are commonly conducted to scrutinize and clarify definitions utilized in literature, as well as to identify and analyze gaps in research, offering valuable insights into the design and conduct of studies on a specific topic (Munn *et al.*, 2018).

From the initial stage of the research, data will be gathered using the Scopus database. Brzezinski (2015) contends that Scopus is a comprehensive database indexing a greater number of sources compared to Web of Science. Table 1 presents the criteria employed for data collection.

Table 1 - Filtering process in Scopus

Date: 03/30/2024	Search	Results
Search field	Title, Abstract, Keywords	
Database	Scopus	
Keywords and Boolean terms	TITLE-ABS-KEY (("circular economy" OR "green IT" OR "recycl* IT" OR "IT wast*" OR "electronic waste") AND ("cloud comput*" OR "IaaS" OR "infrastructure as a service" OR "software as a service" OR "SaaS" OR "platform as a service" OR "PaaS" OR "google cloud" OR "microsoft azure" OR "ibm cloud" OR "oracle cloud"))	281
Filter 1 - Time range	Until 2023	266
Filter 2	Articles, Conference papers and Reviews	214

Source: Elaborated by the authors (2024)

The criteria for this research were based on a literature review, which revealed that Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) are the most popular tools in CC, while major companies in the sector include Google, IBM, Microsoft, and Oracle. Therefore, the selected keywords for this study were focused on these main CC tools and platforms. The time range for the search extended up to December 31, 2023.

Additionally, considering that the concept of CE is still evolving in academia and may have conflicting definitions, mainly regarding to the integration of CC, other keywords were included in the search, such as green Information Technology (IT) and electronic waste, as these elements are closely connected to CE themes. Furthermore, only articles and reviews were considered in the sample for analysis.

After completing the systematic selection of articles and conducting descriptive analysis, the data was exported to VOSviewer software, an open and free computer program used to construct and visualize bibliometric maps. VOS stands for "visualization of similarities," and the program can generate maps using VOS mapping techniques or multidimensional scaling (Van Eck; Waltman, 2014). A co-occurrence of keywords map was created to visualize the connections between keywords in the research field. Such a map can illustrate the pathways, whether temporal or not, in which the research field is evolving by depicting the

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connections between keywords based on their distances. Keywords that are closer together are considered more closely related (Van Eck; Waltman, 2014; Župic; Čater, 2015).

The third and final step is related to the ReSOLVE framework, which involves verifying circularity systems (Ramakrishna et al., 2020). The ReSOLVE framework acronym stands for Regenerate, Share, Optimize, Loop, Virtualize, and Exchange. All analyses will be conducted based on the discussions already presented in the descriptive analysis of the market. The methodology will be adapted from the works of the Ellen MacArthur Foundation (2013) and Ramakrishna et al. (2020) and will follow the criteria described in Table 2.

Table 2 - ReSOLVE framework adapted to a CC environment

Action	Description
Regenerate	Actions by the analyzed companies involved shifting to renewable energy and materials, ecosystem health, and integrating biological resources into the biosphere
Share	Sharing, reuse, and maintenance
Optimize	Efficiency, waste management, big data, automation
Loop	Remanufacturing, recycling, anaerobic digestion, organic waste extraction
Virtualize	Dematerialize directly and/or indirectly
Exchange	Replace materials, new technologies, new products

Source: Adapted from Ramakrishna et al. (2020)

Table 2 summarizes the concepts regarding the classification of the content adapting ReSOLVE framework to a CC initiative.

At first, all the abstracts of the documents were fully read to be selected in the study object of intersectionality of CC and CE. All the content (articles or reviews) selected to become part of the ReSOLVE framework (previously selected) was passed through a peer-reviewed process, wherein, at least one of the authors selected and read the relevant papers from the data previously collected. It is important to point out that all papers lay on the "Virtualize" of ReSOLVE framework, however only papers presenting a technical approach related to virtualization were included in this label.

The articles included in the final sample reflect the main solutions to CE. While cost reductions, security solutions, case studies, or reviews are important in literature, they are beyond the scope of this article. Additionally, articles that were not publicly available or were incomplete were not considered. Articles not written in English were also excluded from the sample.

RESULTS

As mentioned in the methodology section, the results will be divided into an overview of the Scopus search, followed by a co-occurrence bibliometric map. Lastly, a ReSOLVE framework will be derived from the papers selected in the previous search. Figure 1 illustrates the number of publications related to the themes searched in Scopus.

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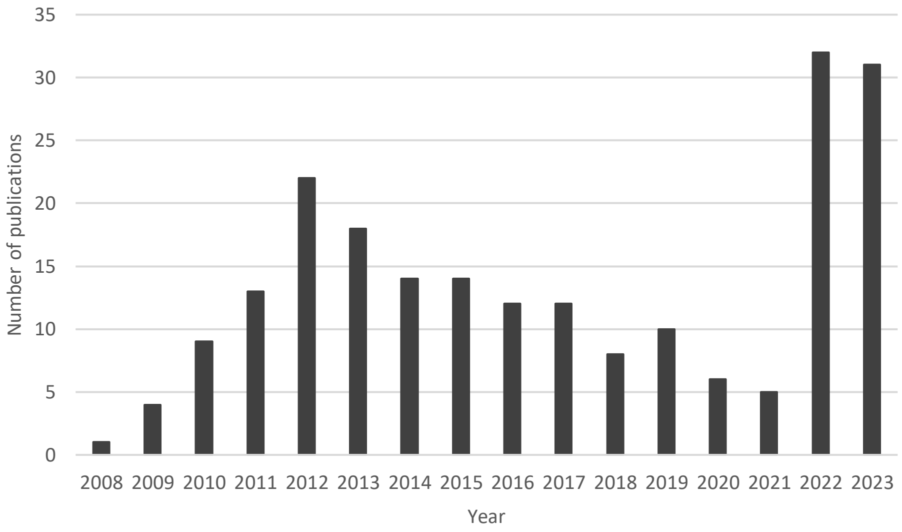
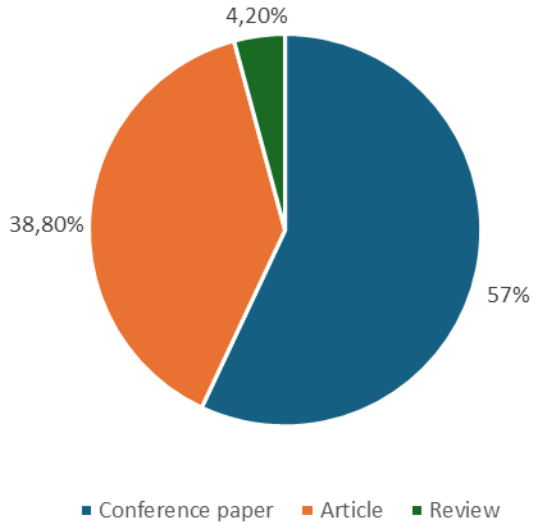
Figure 1 - Number of publications from cloud computing and circular economy gathered in the systematic scoping review



Source: Elaborated by the authors (2024)

Starting in 2010, there was a significant increase in publications, maintaining an average above 2 until 2018, when the number of publications decreased to around 1. However, in 2019, it recovered (Figure 1). This phenomenon could be attributed to the specific keywords used in the research. It is also noteworthy that most papers were published before the 2020s, but the real peak of publications occurred in that decade. Overall, the number of publications from 2010 tends to be at least 4, except when it surged to over 30 publications per year from 2022 onwards. Figure 2 depicts the distribution of document types collected.

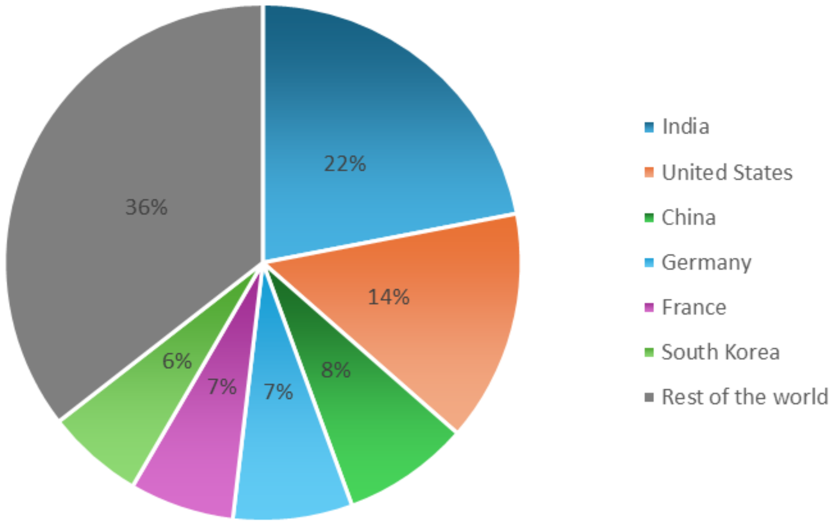
Figure 2 - Document types of publications collected from 2008 and 2023



Source: Elaborated by the authors (2024)

Figure 2 evidence that most documents in the sample are Conference papers. This could be due to various factors such as publication preferences or the time it takes for papers to be published, but it does not necessarily imply anything specific to our research; it merely helps us understand our sample better. Figure 3 shows the proportion of documents published by countries.

Figure 3 – Proportion of documents per country



Source: Elaborated by the authors (2025)

Most of the publications in the sample come from countries in the Global North, mainly developed and wealthy nations. However, India and China also stand out, with 22% and 8% of all publications, respectively. This is interesting because India is a major technology center in the world and China has been frequently associated with sustainable development initiatives. As Lewis (2007) notes, India leads the developing world in the production of large wind turbines, with China following closely behind. These findings suggest that science and technology initiatives may serve as important catalysts for advancing circular economy (CE) practices and broadening sustainable development goals.

Figure 4 presents an overlay visualization of a keyword co-occurrence map, showing the linkage strength of 7 keywords from the 214 documents gathered previously, resulting in a total of 66 keywords.

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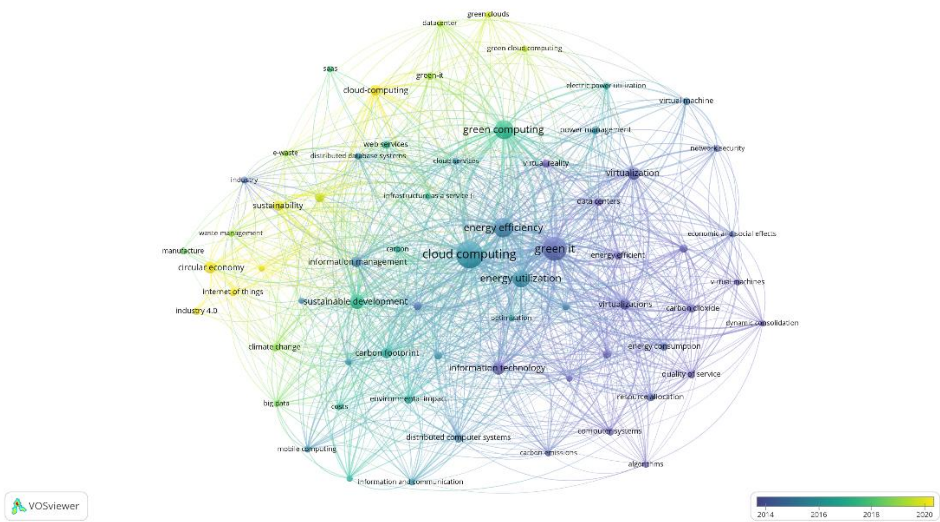
Figure 4 - Overlay visualization from co-occurrence analysis



Source: Elaborated by the authors (2024)

From the co-occurrence map, there is a clear shift in research themes within the area studied. Between 2014 and 2016 (blue), the themes are predominantly related to energy and virtualization. However, closer to 2018, there is a noticeable focus on waste and environmental issues, such as greenhouse gases. CE itself only emerges from 2020 onwards, suggesting a possible popularization of the theme during that period. This shift indicates that the line of research is becoming more specialized, targeting increasingly specific themes related to climate change and CE models. Table 3 presents the clusters identified in the analysis, organized by linkage strength. The analysis was conducted with a minimum occurrence of a keyword set at 8. The VosViewer was configured to employ a resolution of 1.5 and a minimum cluster size of 5 items.

Table 3 - Clusters identified in the keyword analysis grouped by linkage strength

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Artificial intelligence	Algorithms	Carbon footprint (carbon)	Electric power utilization	Carbon emissions	Cloud services
Big data	Carbon dioxide	Cost effectiveness (cost reduction, costs)	Green computing	Cloud computing	Cloud computing
Circular economy	Computer simulation	Digital storage	Network security	Computer systems	Data center
Climate change	Dynamic consolidati on	Distributed computer systems	Power manageme nt	Computer resource	Distributed database systems
Electronic waste (e-waste)	Economic and social effects	Information and communicatio n technologies	Virtual machine	Data centers	Green cloud computing

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Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Industry (industry 4.0)	Energy consumpti on	Information management	Virtual reality	Energy eficiente	Green clouds

Source: Elaborated by the authors (2024)

The clusters identified in Table 3 though keyword analysis offer a broad view of modern technology research. Understanding these clusters can help guide decisions and research directions in academia and industry. Cluster 1 focuses on advanced technologies like AI and big data, with a growing emphasis on sustainability. Cluster 2 highlights energy efficiency, while Cluster 3 deals with data systems and cybersecurity. Cluster 4 explores computer resource management, and Cluster 5 demonstrates the extensive use of cloud services. Lastly, Cluster 6 emphasizes the link between technology and environmental sustainability, especially in green computing. It is seen that many keywords are related to technologies employed, especially "datacenters". This is expected because of the Boolean operators used in this approach, only in Cluster 1 keywords such electronic waste and climate change, a more interdisciplinary approach are being explored.

Many studies have evaluated the feasibility of Green IT from various perspectives, including economic (Geetanjali; Quraishi, 2022; Jie *et al.*, 2016) and social (Hidalgo-Crespo and Riel, 2023), as well as operational concerns like security (Grossman, 2011). Despite Cluster 1, there is a biased focus on energy efficiency, as evidenced by the number of keywords in each cluster that focus on consumption, cost reduction, and management. While there is a wealth of research in this area, our focus in this paper is more specifically on the applicability of CC in the CE context. Therefore, we initially collected 214 documents using a combination of Boolean operators, time range restrictions, and document type filters. Following a rigorous peer-review process involving analysis of titles and abstracts, we narrowed down the selection to 92 documents.

After thorough examination of the full texts, only 33 documents remained, aligning closely with the scope of our research. From this final subset of 33 documents, our analysis focused on evaluating how features of CC facilitate the transition to a CE. Table 4 provides an overview of the key findings, illustrating the relationship between CC environments and CE drivers as outlined in the ReSOLVE framework.

Table 4 - Circular Economy applied in a CC environment

Action	Examples by diferent authors
Regenerate	Ultrasonic sensors (Fisher et al., 2020)
Share	Sustainable mobility (Pulselli; Broersma; Dobbelsteen, 2021)
Optimize	Energy-saving (Ruth, 2011, Lamb and Marimekala, 2013, Ajmera; Tewari, 2018; Basmadjian, 2019; Tai; Lin; Hsiao, 2023); High Performance Computing (Garg et al., 2011; Cappiello et al., 2016); Performance aware resources (Beloglazov; Abawajy; Buyya, 2012); Virtual machine consolidation (Hasan and Huh, 2013); Mobile CC (Zapater et al., 2014); Jam position (Park and Jeong,

Action	Examples by diferent authors
	2014); Genetic Algorithm (Moghaddam; Moghaddam; Cheriet, 2012); Load conditions relationships (Xavier et al., 2017; Shanmugam; Iyengar, 2019; Kumar et al., 2022); Data driven models (Fisher et al., 2020; Ma et al., 2020; Kazancoglu et al., 2021); Auction scheme (Singhal and Singhal, 2021); Shower panel (Czajkowski et al., 2021); Food waste management (Manjunath and Shah, 2019), Food waste management (Singhal et al., 2019; Ergeldi and Feyzioglu, 2023).
Loop	Dairy supply chains (Kazancoglu et al., 2021), Cloud remanufacturing (Caterino et al., 2022).
Virtualize	Data centers (Ruth, 2011; Garg et al., 2011); bits (Ruth, 2011); Security (Li et al., 2012); Virtual Data Centers (Amokrane et al., 2013); Technology integration in dairy supply chains (Kazancoglu et al., 2021); Food waste management (Manjunath and Shah, 2019), Smart green infrastructure (Lamb and Marimekala, 2013), Business process as a service (Yongsiriwit; Assy; Walid, 2016), Green healthcare (Godbole and Lamb, 2018).
Exchange	Atoms for bits swap (Ruth, 2011); Home assisted living (Zapater et al., 2014); Mimetics (Moghaddam; Moghaddam; Cheriet, 2015); Cloud manufacturing (Wang; Wang; Gao, 2013; Wang and Wang, 2017); Intelligent manufacturing (Ma et al., 2020); Water and waste reduction (Pulselli; Broersma; Dobbelsteen, 2021; Czajkowski et al., 2021; Sadri; Khakpoor; Shokouhi, 2020), Digital Life Cycle Passport (Plociennik et al., 2022), Cloud remanufacturing (Caterino et al., 2022).

Source: Elaborated by the authors (2024)

Most papers in Table 4 are classified under the “Optimize“ and “Exchange” actions of ReSOLVE’s framework representing 72.73%, without considering duplicates. Since 2016, there has been a diversity of themes, as evidenced by the bibliometric results. Each of the Share and Regenerate topics is represented by only one article. Furthermore, the bulk of papers remaining in the sample date back to 2015, indicating a concentration on energy efficiency, as highlighted in the bibliometric analysis. From Table 4, out of the 12 subtopics identified within the “Optimize” action, ten are directly related to energy efficiency. These cover energy-saving strategies, improvements in computing efficiency (including HPC, mobile cloud, and virtual machine management), algorithm-based approaches (such as genetic algorithms and data-driven models), resource-aware scheduling, and context-specific solutions like traffic jam positioning and load-energy analysis. The other two subtopics, smart household technologies (e.g., shower panels) and food waste management, are indirectly connected to energy efficiency through their contributions to broader sustainability goals.

Other aspects of climate change advocacy for CE and sustainable development have been predominantly studied from 2015 onwards. Additionally, the term "Green IT" is frequently used to encompass the broader concept of ICTs, with climate change being integrated into it mainly through the promotion of feasible virtualization in infrastructure (Lamb, 2011). Fisher *et al.* (2020) suggest leveraging technology, such as ultrasonic sensors, to enhance anaerobic digestion processes and industrial operations by controlling temperature. They emphasize the role of CC and data utilization in simplifying complex processes. This is the only document addressing the “Regenerate” action, in the subtopic of “Ultrassonic sensors”.

Pulselli, Broersma, Dobbelsteen (2021) propose fostering better cities by addressing economic, social, and technological aspects, citing Roeselare, Belgium, as an example where sustainable mobility initiatives aim to reduce GHG emissions. Kazancoglu *et al.* (2021) focus on using big data to optimize dairy supply chains for CE goals, emphasizing CC's role in production management and resource allocation. Caterino *et al.* (2022) discuss cloud remanufacturing infrastructure, advocating for integrating life cycle assessments to promote sustainability in industrial processes.

The effectiveness of data-driven models (DDM) has been demonstrated in several studies (Fisher *et al.*, 2020; Ma *et al.*, 2020; Kazancoglu *et al.*, 2021), primarily through system optimization and improved decision-making. Fisher *et al.* (2020) explored the potential of DDMs to implement CE principles, enhance process resilience, and value waste by identifying relationships between system state variables, even without prior knowledge. Similarly, Kazancoglu *et al.* (2021) applied DDM in dairy supply chains, while Ma *et al.* (2020) utilized data to integrate intelligent manufacturing for cleaner production, aligning with CE strategies.

Another strategy involves implementing virtual data centers (Garg *et al.*, 2011; Amokrane *et al.*, 2013) and high-performance computing (HPC) (Garg *et al.*, 2011; Cappiello *et al.*, 2016), primarily targeting energy and profit efficiency. This explains why optimization and virtualization are the focus of the papers analyzed, which aligns with the keywords identified in the co-occurrence map, emphasizing optimization and virtualization. Additional approaches include smart energy-saving through automation in powering machines (Beloglazov; Abawajy; Buyya, 2012; Xavier *et al.*, 2017) and the development of auction schemes for equitable request distribution in CC management systems (Singhal and Singhal, 2021).

A feature highlighted by many authors in CC systems (Fisher *et al.*, 2020; Ma *et al.*, 2020; Czajkowski *et al.*, 2021) is their ability to provide real-time responses. This capability helps to prevent potential risks to the system itself, or the production processes it supports, and it can also enhance security measures in CC environments. Li *et al.* (2012) proposed a virtual machine security service based on security isolation, trusted loading, monitoring, and detection. In their system, if a virtual machine is attacked, it will be highlighted in red. Similarly, Czajkowski *et al.* (2021) investigated the security of a shower panel's remote control by programming it to send real-time information about hygiene fluids, device operating parameters, water consumption, and other relevant data.

Further analysis of case studies, such as the one conducted by Czajkowski *et al.* (2021), reveals the development of a prototype interactive shower panel for households or hotels. This prototype enables real-time data collection for evaluating system performance, including minimizing water usage, increasing profitability, and reducing the incidence of certain bacteria through temperature control. Additionally, Zapater *et al.* (2014) introduced a mobile CC solution for electronic health services called Home Assisted Living. This system primarily focuses on tracking and analyzing cardiovascular health, aiming to address two main issues in healthcare systems: reducing healthcare costs through prevention and empowering patients. This empowerment is particularly crucial in underdeveloped countries where access to nearby hospitals and diagnostic accuracy may be limited.

The role of CC in underdeveloped countries may be underestimated, given the limited number of publications on this topic. Some papers have attempted to explore the integration of CC in underdeveloped scenarios (Ma *et al.*, 2020; Kazancoglu *et al.*, 2021; Pulselli, Broersma, Dobbelsteen 2021). The main issue concerning this theme is adaptation; not all proposals are suitable for the reality experienced in regions with high levels of inequality or extreme poverty. Additionally, the importance of government or central entities in effectively distributing and financing such technologies to the population has been emphasized. However, it is important to note that in other countries, such as India and China, there is a movement toward publication (Figure 3), indicating that these issues are likely to be addressed soon.

It is also interesting to note the evolving focus of articles over time. Since 2014, authors have shown a growing concern with defining green mechanisms. Park and Jeong (2014) emphasize that green entails reduced energy consumption, increased recycling and reuse, waste reduction, minimized water usage, pollution reduction, and natural resource preservation. Czajkowski *et al.* (2021) highlight the significance of cleaner production to counter linear economy practices. Additionally, there's a trend towards biomimetics, with algorithms mimicking genetic logic to optimize solutions for CC systems, as demonstrated by Moghaddam *et al.* (2015).

At last, but not least, there are manufacturing solutions (Wang; Wang; Gao, 2013; Wang and Wang, 2017; Ma *et al.*, 2020) and evaluations of CC systems (Hasan and Huh, 2013; Xavier *et al.*, 2017; Basmadjian, 2019). The primary distinction between manufacturing CC and CC itself lies in the integration with physical machines. Ma *et al.* (2020) proposed a data-driven sustainable intelligent manufacturing approach to address energy-intensive industries, while Wang, Wang, and Gao (2013) implement a remanufacturing cloud infrastructure to reduce electronic and electric equipment waste.

Hasan and Huh (2013) and Xavier *et al.* (2017) used a simulation toolkit entitled CloudSIM to measure virtual machines effectiveness, while Basmadjian (2019) developed some metrics to integrate a CC system such as green energy coefficient and green power usage effectiveness. These two metrics may help to manage data centers and cope with an eco-friendly and technological environment.

DISCUSSION

Optimization emerges as a central strategy within the context of CC. As shown in Table 4, approximately 39.39% of the analyzed articles are classified under the "Optimize" action; however, the nascent exploration of concepts like Regenerate, Share, and Loop within the ReSOLVE framework underscores the need for broader perspectives. Despite CC's alignment with Information and Communication

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Technology (ICT), there's a necessity to reassess resource usage in infrastructure technologies and consider alternative energy sources such as solar power (Hosman and Baikie, 2013). According to Félix Júnior *et al.* (2023), circular economy (CE) business models need to integrate interdisciplinary research. This is reflected in our analysis: only 36.4% of the documents address at least two different ReSOLVE actions, most often combining "Optimize" with "Virtualize". Notably, only Kazancoglu *et al.* (2021) and Ruth (2011) engage with more than two actions.

Additionally, concerns regarding carbon emissions (Grossman, 2011) and heat dissipation (Yu*; Wu*, 2018) highlight the multifaceted challenges associated with CC implementation. Clusters one, two, three, and five (four out of six) of the keyword clusters in Table 3 demonstrated a number of keywords related to carbon emissions. A response to this issue necessitates not only the use of knowledge from other disciplines (interdisciplinary) but also the incorporation of wisdom from various sectors and individuals, who are stakeholders in general (transdisciplinary). Minervi e*t al.* (2022) explored transdisciplinary into the CE, emphasizing its connection to the social and ecological dimensions of sustainable development. Issues related to software licensing and open service systems (Spellmann; Gimarc; Preston, 2009; Shieh *et al.*, 2011) raise questions about accessibility and social differentiation. These inquiries underscore the necessity of transdisciplinary inclusive approaches to sustainable development.

As evidenced by Kurniawan *et al.* (2023), there has been a surge in publications since 2021, reflecting growing awareness of the challenges in waste management practices. However, the concentration on energy efficiency in our study suggests that critical issues may not be receiving sufficient attention. Cheah *et al.* (2022) and Godbole and Lamb (2018) propose various approaches to integrating CE principles into CC infrastructures, highlighting the potential for technology to address environmental concerns. Encouragingly, initiatives in educational environments, as seen in the work of Mohabuth (2022), Singhal *et al.* (2019), and Hail and Ibrahim (2018), could facilitate broader societal adoption of initiatives related to CC and CE.

Another initiative promoted through the conceptualization of CC is *servicelisation*, as defined by Wang and Wang (2017). By using a logical and physical architecture of CC to reduce electronic waste, the authors conceptualize an efficient infrastructure. *Servicelisation*, beyond its infrastructure, offers a chance to reduce consumption compared to a linear economy by providing services only on demand. The abstraction of CC in a CE society is much deeper than just an approach to energy efficiency and cost reduction.

There are some papers in the collection that stand out from the "optimization" of resource economy by solving specific problems of consumption and production and not the implementation of technology itself. Solutions regarding food waste and water management, such as fruit quality detection (Ergeldi and Feyzioglu, 2023), food waste management in educational institutions (Singhal *et al.*, 2019) and a rational system of water use in hotels (Czajkowski *et al.*, 2021) are certainly a path forward an innovative CC in cooperation with CE. The use of smart technology should not only spare resources from the system but also contribute to an effective use in consumption and production.

From that, is it feasible to integrate the advantages associated with CC with the principles of the CE? From the analysis of articles using CC tools, this integration

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is already happening, indicating a transition to a more sustainable business environment with the utilization of CE principles. However, many of the initiatives are carried out without considering the concept of the CE, thus limiting the extent to which the benefits could be utilized by society. This becomes evident when analyzing performance metrics based on the ReSOLVE model, where there is a concentration on the "Optimize" action. Meanwhile, there are a variety of studies that fall under the "Exchange" item, which offers a range of solutions for the replacement of materials and technological innovations. This could be the closest path to consolidating a CE using technology derived from CC.

On the one hand, this overview reflects what is already discussed in the CE literature, which criticizes the excessive use of recycling because it often does not save resources (Kircherr et al., 2023; Ghisellini; Cialani; Ulgiati, 2016). Many claim to be practicing CE by recycling, but they are not truly doing so. The studies on CC heavily utilize computational resource efficiency, energy dissipation, etc. In other words, there is an overutilization of these techniques and underutilization of other potentialities that CC could offer for sustainable development. On the other hand, those studies offer a broader potential for CE studies in the contribution of optimization of resources, that could be extended beyond systems execution but also to other sectors of the economy.

To successfully use CE with CC, it is important to use interdisciplinary and transdisciplinary methods. This will help to address complex issues and take different actions within the ReSOLVE framework. This approach also allows us to address social and equality issues related to the use of CC. Further topics such as security are still a big worry in CC (Spellmann; Gimarc; Preston, 2009). When using CC, it is important to think about how it will affect the system's architecture and how it will work with other systems (Yongsiriwit, Assyd; Walid, 2016). These multifaceted concerns reinforce the essential role of scientific and technological development in guiding responsible and integrated cloud computing solutions.

CONCLUSION

In summary, the aim of this study was to investigate the integration of CE principles within the realm of CC and to explore how CC can facilitate sustainable practices. This study presents a scoping review and bibliometric analysis of the literature on the role of cloud computing (CC) in fostering circular economy (CE) strategies.

It is evident from our analysis that CC serves as a crucial enabler of CE, offering opportunities for resource optimization, waste reduction, and sustainable practices across various sectors. From our research, a sample of 33 articles that were classified according to the ReSOLVE Framework of CE was selected. Although there is a significant concentration of documents within the "Optimize" and "Exchange" actions, there is also a large contribution within each action. The utilization of virtualization, optimization algorithms, and data-driven models in CC systems can contribute to the circularity of processes and minimize environmental impact.

The temporal evolution of the themes indicates a shift from a focus on virtualization and energy towards broader issues of sustainability and circular economy from 2020 onwards. Despite this thematic diversification, there remains

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a significant gap in the "Share" and "Regenerate" actions, which are underrepresented among the analyzed articles. This uneven distribution suggests future research opportunities, particularly aimed at collaborative and regenerative applications of digital technologies, such as sensors, sustainable mobility, and integrated urban models.

While we are witnessing a transition towards CE, particularly driven by advancements in energy efficiency within CC infrastructures by analyzing this new mapping of CC integrating CE, further concerted efforts are required to fully realize the potential of this transition. Overcoming challenges such as interoperability, security concerns, and regulatory frameworks will be pivotal in accelerating this transition. To fully leverage CC as a driver of CE, it is essential to move beyond efficiency and embrace interdisciplinary and transdisciplinary strategies that account for social, ecological, and ethical dimensions. Only through such integrative efforts can CC contribute meaningfully to a circular, inclusive, and resilient economy.Some limitations of our study include the reliance on English-language literature and the focus primarily on peer-reviewed articles. Additionally, the exclusion of non-English articles may have led to the oversight of valuable insights from non-English-speaking regions. Our findings suggest that while there has been significant progress in aligning CC with CE principles, there is a need for more comprehensive metrics to measure the effectiveness of such integration. The ReSOLVE framework may not be sufficient to systematize CE-driven initiatives within CC environments, for that the development of such metrics could provide valuable insights into their impact and scalability.

Future studies could expand the knowledge regarding the role of emerging technologies, such as blockchain and artificial intelligence, in advancing CE within CC environments. Furthermore, comparative studies across different regions and industries could provide a more comprehensive understanding of the global landscape of CC-CE integration, contributing to filling the knowledge gap to assess such integration.

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