

Review

The Role of the Triple Helix Model in Promoting the Circular Economy: Government-Led Integration Strategies and Practical Application

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Abstract: The Circular Economy (CE) has become an essential management model to address the environmental challenges of the traditional linear model employed by companies, protecting society and ecosystems from resource depletion and intensified ecological emissions. Thus, this study proposes a framework with recommendations for CE implementation, structured around the Triple Helix (TH) model and designed to be government-led in guiding joint actions among government, organizations, and academia. The framework comprises 21 recommendations distributed across six interconnected stages: (1) Policy Generation from Academic Inputs, (2) Development of Pilot Projects with Industry, (3) Analysis and Academic Validation of Results, (4) Policy Improvement and Scaling, (5) Promotion of Innovation and Technology Transfer, and (6) Global Connection and Replicability. These stages collectively enhance policies and practices, accelerating the transition to a CE. This framework underscores the importance of regionally adapted public policies, technological innovations to extend material lifespans, and the promotion of conscious consumption. It also emphasizes the need for intersectoral collaboration to foster sustainability and efficiency in resource management. Methodologically, this study employs an integrative review to map technical and scientific CE practices in the United Kingdom, China, and the United States. The theoretical contribution validates the TH model as a strategic tool for developing the CE. Furthermore, the practical contribution is the structured pathway to implementing the CE, detailing the main phases of collaboration among TH actors to ensure the effective operationalization of circular strategies.

Keywords: circular economy; Triple Helix; sustainability; government leadership; public policies



Academic Editor: David J. Tonjes

Received: 24 January 2025

Revised: 10 March 2025

Accepted: 13 March 2025

Published: 20 March 2025

Citation: Espuny, M.; Reis, J.S.d.M.; Giupponi, E.C.B.; Rocha, A.B.T.; Costa, A.C.F.; Poltronieri, C.F.; Oliveira, O.J.d.

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Strategies and Practical Application. *Recycling* **2025**, *10*, 50. <https://doi.org/10.3390/recycling10020050>

Recycling **2025**, *10*, 50. <https://doi.org/10.3390/recycling10020050>

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1. Introduction

The increasing pressure on the planet’s natural resources has been highlighted annually by Earth Overshoot Day (EOD), which marks when humanity has consumed all renewable resources available for that year [1]. This scenario results from population growth, intense urbanization, excessive consumption, and planned obsolescence, particularly in wealthy nations [2]. As a result, the rising global demand for food, water, energy, and other raw materials intensifies resource depletion. It threatens the Planetary Boundaries, increasing

the risks of freshwater scarcity, soil degradation, biodiversity loss, and other environmental pressures [3–11].

Considering the challenges posed by unsustainable production and the continuous increase in waste generation, the Circular Economy (CE) model offers a conceptual solution by eliminating waste and allowing resources to circulate in use at their highest value [12]. Initiatives such as the Kalundborg Eco-Industrial Park in Denmark, where industrial by-products are recycled and reused among collaborating companies [13]; the Netherlands' National Circular Economy Strategy, which aims for full circularity by 2050 [14]; and the European Green Deal, which revises waste policies and promotes circular solutions across sectors [15], illustrate the transformative potential of closing resource loops in alignment with CE principles.

A coordinated effort among various stakeholders is necessary for society to adopt circular solutions widely. In this sense, the Triple Helix (TH) model advocates the simultaneous work of government, industry, and academia to drive eco-innovation [16,17]. According to this model, public policies can stimulate industrial initiatives, while scientific research generates knowledge to develop more sustainable and circular technologies and practices. This synergistic relationship is vital in sectors such as metal manufacturing, where university research on lower-impact processes depends on government support and corporate engagement to translate innovations into real-world applications [18].

The TH model strengthens innovation by reinforcing partnerships for government, organizations, and academia. It allows new ideas generated in laboratories and classrooms to be swiftly tested and commercialized with the legislative framework's support [19]. Notable success stories include joint efforts among Stanford (university), the government of the Silicon Valley region, and technology giants such as Google, Apple, and Facebook. In developing countries, similar partnerships can foster technological and industrial hubs, as exemplified by the city of São José dos Campos, Brazil, where the Air Force (government), Embraer (organization), and the Institute of Technology (academia) have collaborated to establish a competitive aerospace ecosystem [16,19].

Similarly, when applied to the CE, the TH model policies and legislation promote responsible consumption and waste management (e.g., electronic waste disposal). They also foster academic research to enhance recycling technologies and drive industrial initiatives, enabling new circular business models [20,21]. Several studies have explored how the TH structure supports the development of the CE in different contexts. Ref. [22] empirically examined how the CE is conceived in the institutional spheres of government, industry, and academia, emphasizing the importance of building consensus to identify innovation opportunities. Ref. [23] highlighted how the Welsh government promotes the CE by cultivating professional groups called Communities of Practice (CoPs) to connect various industrial sectors. These groups exemplify collaboration among government, industries, and universities, facilitating knowledge sharing and the creation of practical solutions to CE-related challenges. Ref. [24] analyzed the challenges small and medium-sized enterprises (SMEs) face in achieving environmental innovations and reducing financial risks associated with investments in circular activities. The integration of SMEs with universities and government policies exemplifies the operationalization of TH in overcoming these challenges.

Ref. [25] investigated entrepreneurship from the perspective of the CE, focusing on waste collection in Portugal. The authors found that compliance with waste management laws has driven innovation in SMEs. This study highlights how the interaction among companies, government policies, and research institutions fosters an environment conducive to circular innovation. Ref. [26] argued that urban governance should encourage circular dynamics based on sharing information, making strategic decisions, and involving

stakeholders. Using urban regeneration in Siracusa, Italy, as a case study, the authors demonstrated the importance of collaboration among TH entities to achieve sustainable urban outcomes.

Although several studies discuss parts of this tripartite interaction, a gap exists regarding how governments can take the lead in driving actions to promote the CE. This includes defining incentive policies, providing adequate regulation to encourage circular practices, and aligning industry needs with academic support [25,26]. Thus, the main question of this study is “How can governments successfully implement Circular Economy practices by working with businesses, universities, and public organizations to create effective policies, encourage circular industry practices, and support research, all while ensuring that their actions are coordinated and sustainable?”.

To answer this question, this work aims to propose a framework, guided by the TH model, that guides the adoption of CE practices under government leadership, promoting structured cooperation between government, industry, and academia. This way, we will generate a framework for implementing TH interaction to achieve successful CE programs.

2. Theoretical Referential

Since the Industrial Revolution, the dominant economic model has been the Linear Economy (LE), characterized by a “take–make–use–dispose” approach [27–30], as illustrated in Figure 1.

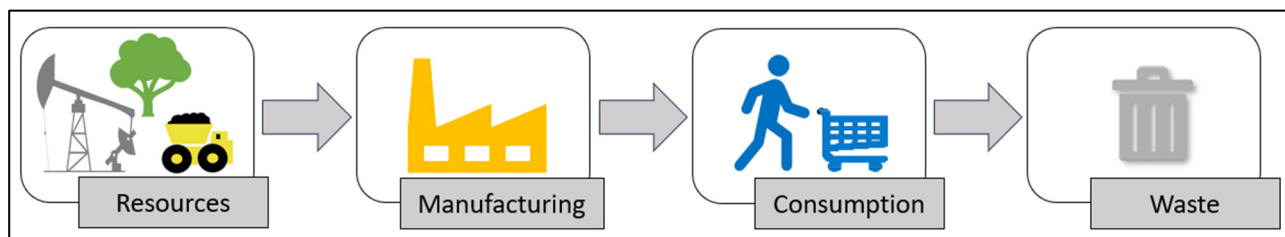


Figure 1. Linear Economy. Source: [29].

However, decades of industrial production following the LE model and rising global consumption have led to severe environmental consequences. These include heightened greenhouse gas (GHG) emissions, widespread water and soil pollution, and the accelerated depletion of natural resources [31–33]. In contrast, the CE has emerged as a business model that reintegrates discarded materials after consumption into the production cycle [34–36]. This regenerative approach [37–39] reduces the extraction of natural resources, energy consumption in manufacturing, and waste disposal [28,40–44]. However, implementing the CE does not automatically ensure positive sustainability outcomes. According to [45], there are trade-offs between material reuse cycles and the different dimensions of sustainability—environmental, economic, and social. Studies indicate that companies often disregard circular strategies (CSs), such as recycling and reusing, when clear financial benefits are not evident, even if these practices are environmentally beneficial. Therefore, developing economic indicators to assess the impact of the CE is essential for measuring its effectiveness and encouraging broader adoption.

Despite the challenges faced by industrial, governmental, social, and academic sectors, many companies are striving to transition from the LE to the CE [33,46,47] due to its potential to generate economic, environmental, and social benefits, aligning with the sustainable development tripod [37,48–50]. The CE aims to close the material flow cycle by reprocessing products discarded by end consumers and reintegrating them as inputs, thereby preserving and regenerating virgin materials [51–53], as illustrated in Figure 2.

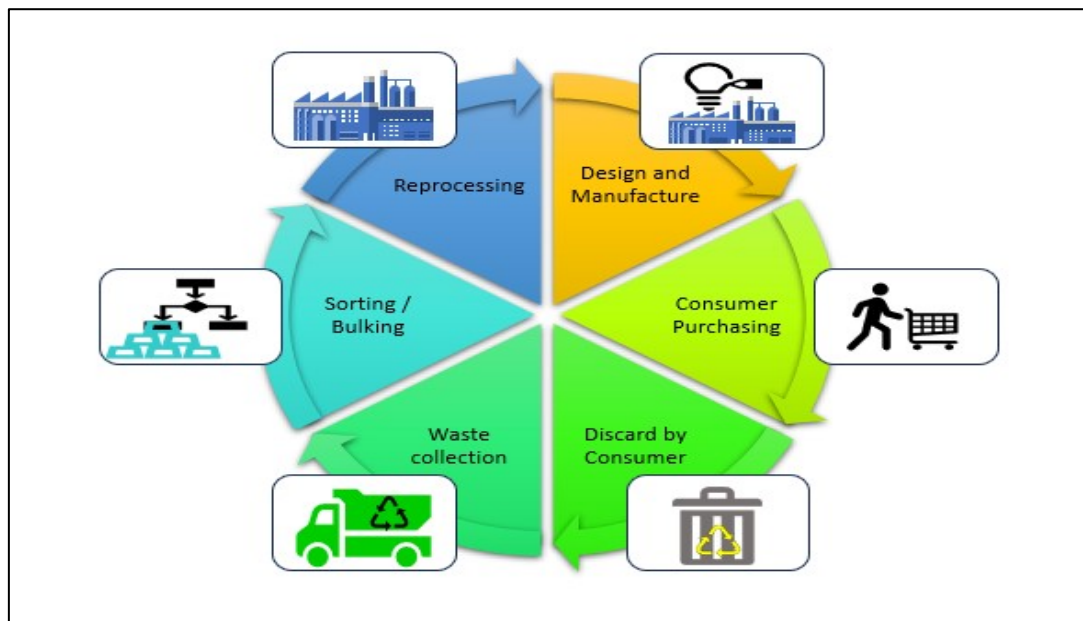


Figure 2. Circular Economy. Source: Adapted from [54].

The CE also drives economic growth by reducing dependence on finite natural resources and fostering sustainable business models. Studies indicate that European countries adopting circular policies, such as Germany, the United Kingdom, and the Nordic nations, have experienced positive effects on GDP, raw material supply security, and job creation [55]. However, transitioning to a CE requires restructuring production models and enhancing coordination among governments, organizations, and society to overcome regulatory and operational barriers.

In this context, adopting circular strategies goes beyond reformulating production processes; it also requires applying principles and concepts that underpin the CE. The CE integrates the 3Rs principle (Reduce, Reuse, Recycle) alongside industrial ecology, eco-design, cradle-to-cradle, the sharing economy, and zero waste to enhance sustainability outcomes [45,46,49], as outlined in the objectives presented in Table 1.

Table 1. Concepts related to CE.

Concepts	Definition	Objectives
3Rs (Reduce, Reuse, Recycle)	The 3Rs are fundamental principles for minimizing waste and managing resources efficiently, promoting sustainability and the CE [37,47].	Minimize the consumption of materials and energy in production processes; promote conscious consumption through the reuse of goods; and reprocess materials to maximize the use of what would otherwise be discarded [27,34,47].
Industrial Ecology	Industrial ecology applies principles inspired by natural ecosystems to industrial environments [56].	Enhance the efficiency of industrial processes by minimizing waste generation and striving for the high-quality standards observed in nature, replicating the biological interactions of natural ecosystems within industrial systems [57,58].

Table 1. *Cont.*

Concepts	Definition	Objectives
Eco-Design	Developing products that maximize material reprocessing and reuse, minimizing environmental impact throughout their life cycle [59].	Develop products that prioritize ecological considerations throughout their entire life cycle, including post-disposal, while preserving quality and value for as long as possible and minimizing raw material consumption [59–61].
Cradle-to-Cradle	Implement reusable materials in production, ensuring that discarded products can be reintegrated as inputs in new manufacturing cycles, creating a closed-loop system [62].	Encourage manufacturers to take responsibility for collecting and processing waste generated after product use and disposal, ensuring its reintegration into the production cycle [56,63].
Sharing Economy	Leverage digital platforms to enable the collaborative sharing of goods and services, optimizing resource use and reducing waste [64].	Facilitate the cooperative acquisition of goods and services to reduce purchasing and maintenance costs while promoting lower resource consumption [51,65].
Zero Waste	Eliminate waste generation by optimizing resource use and designing systems that prevent waste at every stage, minimizing environmental impact [27].	Optimize resource consumption (materials, energy, and water) while reducing waste sent to the environment. In production systems, lean manufacturing practices support the achievement of zero waste by improving efficiency and reducing waste generation [66].

One of the main challenges of the CE is its relationship with industrial innovation. According to [67], the CE promotes longer product life cycles, which can conflict with an economic model focused on constant innovation and the frequent launch of new products. To address this, researchers have explored emerging technologies such as the bioeconomy and additive manufacturing (3D printing) as potential solutions for creating a production model that is both innovative and circular, enabling more efficient use of materials and reducing environmental impact. The CE fosters technological development by driving innovation to enhance industrial processes, particularly in material transformation for reuse and improving productivity and resource efficiency [68–70].

The CE contributes to the economic, environmental, and social aspects of sustainable development in several ways, including (a) job creation and income generation through the growth of companies involved in waste collection, sorting, and processing [34]; (b) reducing the consumption of primary resources [60,71]; (c) mitigating price volatility in the acquisition of recycled inputs compared to natural resources, due to scarcity [28,33,56]; (d) reducing energy consumption in industrial processes by preventing heat loss [39]; and (e) lowering energy consumption taxes, as taxes on renewable energy sources are typically lower than those on oil and gas [72]. In addition, the authors of [73] emphasize the need to determine how the CE impacts the economy. In this context, they analyzed indicators of the cyclical economy and GDP per capita growth in the European Union (EU). The data show that countries that recycle more urban waste and invest more in research and development achieve higher rates of sustainable development. These actions, in turn, lead companies to reduce production costs [70].

Despite these benefits, numerous challenges remain in transitioning from the LE model to the CE, affecting companies, governments, society, and academia [46]. This transition demands careful planning, strategic adjustments, changes in organizational culture, and operational adaptations to balance environmental preservation and social develop-

ment with economic growth [34,47]. Overcoming these challenges, however, depends on the combined efforts of companies and academia to develop solutions through organizational and technological innovation, governments enacting more effective legislation, and society driving change in consumption behaviors and advocating for more impactful results [69–71].

3. Scientific Method

This applied study aims to provide practical solutions to real-world issues. By focusing on the processes related to the object of study, the research aims to induce change and offer tangible solutions to contemporary challenges. It is descriptive and exploratory, analyzing specific aspects and exploring new opportunities within the topic. As a qualitative study, it facilitates a deeper understanding of the phenomena under investigation and opens avenues for meaningful advancements [74,75].

The study employed the Integrative Review (IR) method to comprehensively search for, identify, select, and analyze documents from various sources [76]. This method is preferable to that of the Bibliometric Study or the Literature Review, which focus more on the quantitative identification of trends, citation networks, and authors and on a more in-depth analysis of scientific documents. In contrast, IR allows for the inclusion of various sources, such as patents, websites, white papers, sustainability reports, etc. [77]. When conducting an IR, researchers must define the research question and objectives, reserving hypothesis formulation for quantitative studies that require testing, which does not apply in this work. The next step involves establishing criteria for the inclusion and exclusion of documents, followed by collecting a substantial amount of material based on the defined parameters. Finally, the collected documents undergo thorough analysis and interpretation [78–80]. The IR supported mapping the CE's Technical–Scientific Scenario (TSS) in this work. The TSS structure allows the exploration of multiple sources of evidence, such as academic articles, leading authors, research funding agencies, patents, company reports, and government regulations. Beyond traditional bibliographic references, these diverse sources enrich the understanding of the current state of knowledge on the subject. Researchers have established rigorous and replicable criteria to standardize the search strategy, selection process, data collection, and information organization to ensure consistency and transparency.

The TSS integrates the TH, a cooperative model that fosters government, organization, and academia collaboration. This model is a powerful tool for identifying contributions and initiatives from these three entities related to the study topic. The ideas from the TSS were used as a guide to create a framework with action plans to promote the CE. This collaborative approach ensured that the study's results encompassed diverse viewpoints and reflected the collective effort in the field. Figure 3 illustrates the five steps of the study, while Appendix A provides detailed information on these steps, broken down into 14 stages labeled A to N (Table A1).

The TSS integrates the TH, a cooperative model that connects government, organizations, and academia. This model serves as a crucial tool for identifying the contributions and initiatives of these three entities regarding the study topic. We used the initiatives identified in the TSS as benchmarking inputs to develop a framework with proposed actions for advancing the CE, as shown in Figure 4.

As illustrated in Figure 4, the development of the framework followed a structured methodological approach, starting with the definition of the study's fundamental elements, as detailed in the next section.

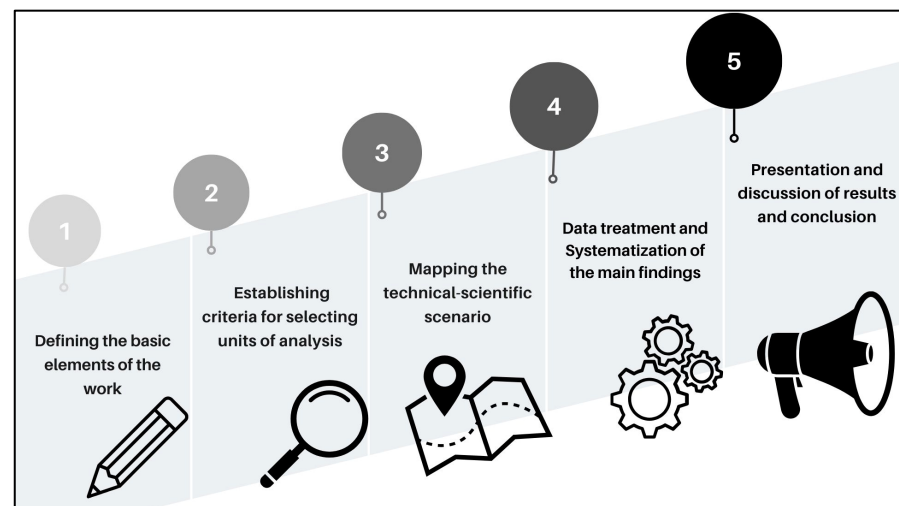


Figure 3. Illustration of the phases of development of the work.

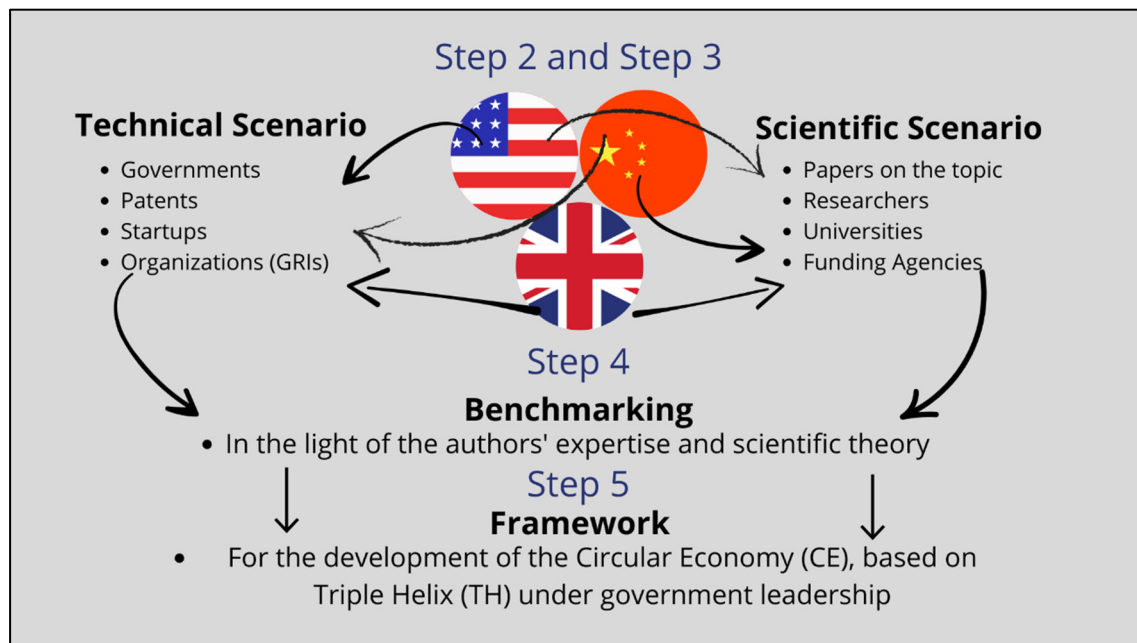


Figure 4. Framework development flow for the CE from the Triple Helix perspective.

3.1. Step 1—Definition of the Basic Elements of the Work

In the first step, we defined the study topic to understand the current state of the art in the CE literature. The initial analysis of relevant articles helped identify specific scientific gaps in the comprehension and implementation of the CE. These gaps included specific gaps, such as a lack of comprehensive understanding of CE principles in particular organizations or insufficient data on the environmental impact of the CE. We formulated the research question based on these findings, and the study's objectives were established [74,81,82]. Additionally, the IR method was selected to map the TSS of the CE, given its ability to provide an integrated view of various sources of information, including articles, patents, and laws, and to incorporate the TH model [83].

3.2. Step 2—Establishing Criteria for Selecting Units of Analysis

In this step, we defined the search parameters for data collection in scientific and technical databases (e.g., Scopus and Lens), focusing on relevant articles and patents related to the CE. Country classification criteria were also determined, considering both

the H-Index (which assesses productivity and academic impact) and the number of patents registered in the CE [20,84,85]. Based on this combination, we identified the final ranking of countries. The United Kingdom, China, and the United States were selected due to their significant contributions and initiatives in the field of the CE, making them the most representative of the scope of the study [86]. Figure A1 illustrates the method used to select these three countries.

3.3. Step 3—Mapping the Technical-Scientific Scenario

After choosing the countries, the next step was to explain the CE situation. This investigation included gathering information from government websites, funding groups, colleges, and reports from large companies. We critically analyzed and interpreted the data obtained from the perspective of the TH model, evaluating the contributions of government, organizations, and academia to the advancement of CE.

3.3.1. Data Sources for Technical–Scientific Mapping

This study incorporated several data sources beyond the academic literature to increase IR inputs on government-led CE development. These sources were carefully selected to capture government, organization, and academia contributions, aligning with the TH model.

In this context, we analyzed influential scientific articles, authors, academic institutions, and research funding agencies in CE research. We also examined patents using the Lens database to identify technological innovations. A total of 208 patents were identified, and the three most relevant were selected based on their recency and direct contributions to the CE.

Beyond academic contributions and patents, we analyzed sustainability reports and business models to clarify how private CE initiatives drive its development and adoption. These reports were selected using [87], identifying the three top-performing companies in the CE sector from the UK and the US and two from China.

We reviewed government policies, regulations, and national and regional laws significantly impacting the CE to assess regulatory frameworks. Priority was given to legislation establishing recycling targets, financial incentives, and resource efficiency standards to understand the legal mechanisms supporting circular transitions. Regarding business models, we analyzed the role of startups as key drivers of innovation, identifying three main trends in each country. In the UK, data from [88] served as the basis for analysis. In China, information was sourced from [89], while the [90] database provided insights for the US. Each startup was selected for its practical contributions to the CE, and a more detailed description is provided in Appendix A.

3.3.2. Data Analysis and Interpretation

A structured analytical process ensured the logical evaluation and categorization of the data collected for this study. Each document was classified based on its contribution to the CE using the TH model, which illustrates the collaboration between government, organizations, and academia in supporting circular initiatives (Section 4).

We examined government rules and policies to assess their impact on CE growth. We reviewed the national and regional legal frameworks to determine how regulations influence circular transitions and industry adaptation.

Within organizations, we analyzed different contributions to the CE. Using the Lens database, we identified patents and technological advancements directly affecting circular practices. We also looked at startups as a source of circular innovation. We selected three companies from each country as examples, drawing from sources such as Circular (UK), Medium (China), and Recycling Startups (USA). The startups were chosen based on

their business models, emphasizing innovative CE approaches. Additionally, we used the Corporate Knights Ranking to analyze corporate sustainability reports (GRIs), selecting the top-performing CE companies from the UK, the US, and China.

We reviewed scientific articles in the Scopus database to analyze the academic sector and identify key authors actively contributing to CE research. Additionally, major funding sponsors of CE-related studies were highlighted, as they are crucial in advancing scientific and technological progress. Lastly, leading universities with significant research outputs in the CE were examined to understand their influence on academic discourse and their role in fostering innovation in circular strategies.

This approach to data analysis enabled the study to identify the main trends shaping the growth of the CE and the conditions necessary to foster collaboration among government, organizations, and academia (Sections 5.1, 5.2, and 5.3). These findings led to the development of 21 strategic recommendations aimed at supporting the structured progress of the CE. To ensure a smooth transition, we created a Roadmap for the Development of the CE, outlining six interconnected stages for implementation. This roadmap provides a step-by-step approach to adopting the CE, ensuring alignment among all TH stakeholders. Section 5.4 offers a more detailed discussion of how to implement these phases.

3.4. Step 4—Data Treatment and Systematization of the Main Findings

In this step, we explored the technical and scientific content of the documents collected from the three countries. We performed a content analysis to group and summarize the innovations, government policies, and initiatives promoted by organizations and academia related to the CE. This process involved specific steps of content analysis, such as data categorization, theme identification, and result summarization. The process culminated in creating the TSS, which systematically integrated the identified elements (e.g., universities and key authors, policies, legislation, patents, and reports), allowing the identification of gaps and opportunities for collaboration [20,83,91]. Combining this information with the authors' expertise supported the development of a framework with collaborative actions between the public and private sectors to promote the CE [82].

3.5. Step 5—Presentation and Discussion of Results and Conclusions

Finally, we presented the framework, which contains 21 recommendations based on the TH model for the development of the CE. We explained these suggestions in detail, emphasizing the significant contributions of governments, organizations, and academia in ensuring the success of the CE. Additionally, we proposed a six-phase roadmap for implementing these recommendations. In this phase, we also answered the research question, situating the findings within the broader context of the study and demonstrating how tripartite collaboration can drive the development of circular practices.

4. Technical–Scientific Scenario

This section presents the Technical–Scientific Scenario (TSS) of the CE between 2016 and 2021 for the three countries ranked highest in the chart shown in Figure 4. The selected countries are the United Kingdom (UK), China, and the United States (USA), as they excel in research and innovation related to the CE. However, these countries still face challenges related to renewable energy generation, effective waste treatment and disposal, and the responsible use of natural resources in line with nature's regeneration cycle [91]. Below are the most relevant actions related to the CE that have made these countries stand out. To facilitate the analysis, the results are divided by country, and within each country, CE initiatives are presented from the TH perspective (governments, organizations, and educational and research institutions).

For government initiatives, considerations include policies, laws, the provision of fiscal and financial incentives, enforcement actions, and the creation of cross-sector partnerships. For organizations, patents, startup innovations, and sustainable actions outlined in GRI reports were identified. The initiatives from educational and research institutions encompass university projects and programs, as well as research funding targeted explicitly at the CE. These funds also support research development through financial incentives.

4.1. United Kingdom

The UK adopted the Circular Economy Package (CEP), created by the EU, to promote circularity across the continent and foster sustainable development through the CE. However, the UK had already made strides in transitioning to the CE before adopting the CEP and developing its policies and initiatives [92]. Government initiatives include drafting laws, setting goals with public participation, and implementing strategies to reduce waste and carbon footprints. Waste management initiatives involve both the private and public sectors as active participants. For example, Scotland’s “Making Things Last” initiative aims to reduce the demand for natural resources within public institutions and universities.

Organizations in the UK have excelled in waste treatment and resource management by transforming waste, developing digital platforms, and creating innovative business models. Academic contributions include aligning the CE with the Sustainable Development Goals (SDGs) and advancing new business strategies. Numerous university–industry partnerships provide theoretical foundations that drive the transition to the CE. Table 2 presents 25 key actions in the UK, categorized according to the TH objectives.

Table 2. CE’s Technical–Scientific Scenario (TSS) in the United Kingdom.

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference
Government	Law—Circular Economy Package policy statement	Creation of the “Resources and Waste Strategy (RWS)” to develop legislation and set goals, with public participation, aimed at reducing waste and inefficiencies. Its objectives include eliminating avoidable plastic use, such as bags, straws, and disposable cutlery; strengthening inspections of final waste disposal; and increasing taxation on companies that do not use recycled plastic.	[54]
		Development of the “Beyond Recycling” strategy to consolidate CE in Wales, targeting zero waste and a reduced carbon footprint. The government supports the green economy in public and private institutions, phases out plastic materials, reduces food waste, and promotes the adoption of low-emission vehicles.	[93]
		Development of the “Delivering Resource Efficiency” strategy to improve waste management in Northern Ireland, increasing efficiency and reducing carbon emissions. Its objectives include strengthening regulation, improving inspections, and optimizing funding allocation for waste management.	[94]
		Creation of the “Making Things Last” strategy to reduce natural resource demand by promoting reuse, recycling, and recovery activities in public organizations, private companies, and universities in Scotland. The government has fostered cross-sector partnerships and implemented measures to increase manufacturers’ accountability for product disposal.	[95]

Table 2. Cont.

TH and Object of Analysis		Topic	Identified Strategies and Actions	Reference
Organizations	Patents	Recycling Method and Taggant for a Recyclable Product	Identification of recyclable product manufacturers through code scanning on packaging to accelerate recycling and ensure proper final disposal.	[96]
		Polyferric sulphate solution	Development of a water filtration and treatment machine that uses oxidation without generating sludge or sediment in reservoirs. This technology enhances the efficiency of treatment plant processes, making them more cost-effective while reducing the discharge of chemicals.	[97]
		Plastic recycling process	Development of a process for extracting color pigments from plastic waste by shearing its surface to produce colorless plastic for recycling. This procedure involves a solvent reactor that deforms the outer layer of the waste, effectively removing the dye from the plastic material.	[98]
	Startups	Gomi	Design and manufacture of products using repaired or recycled materials, ranging from low-value items like plastic bags to more advanced technologies like non-functioning e-bike batteries.	[99]
		Young Planet	Development of an application to encourage the donation of children's products, such as clothes, toys, and accessories, to increase reuse and reduce the demand for natural resources in the production of new items.	[100]
		Full Circle Cambridge	Commercialization of "eco-friendly food and products" that reduce plastic packaging and contribute to zero waste, minimizing environmental impacts. The company offers vegan products in bulk, encouraging customers to bring their containers for purchases.	[101]
	GRIs	Atlantica Sustainable Infrastructure	Implementation of waste-reduction techniques, including leak detection, employee training to minimize waste, and constructing bioremediation areas for contaminated soil. The company also significantly reduced hazardous waste generation by improving material management, recycling, and implementing ISO 14001 standards.	[102]
		Unilever	Use of reusable, recyclable, or compostable materials in product packaging. The company reduced virgin plastic use by half and increased the use of recycled plastic as raw material. Major Nigerian cities have established collection points for plastic waste to encourage proper disposal.	[103]
		BT Group	Establishing partnerships for reusing and recycling electronic equipment and cables discarded by customers and recovering gold from damaged electronic boards.	[104]
Academia	Articles		Development of a "Toolbox" for implementing SDGs through CE practices, highlighting significant impacts on Goals 6, 7, 8, 12, and 15.	[37]
			Development of a circular business model integrating web technologies, reverse logistics, and additive manufacturing to support CE practices. This approach reduces resource consumption and environmental impacts while promoting local business networks and job creation.	[105]
			Global economic restructuring study advocates replacing the current linear model with the CE for greater resilience and sustainability, especially post-COVID-19 recovery. Provides sector-specific recommendations to balance profit with minimal environmental impact.	[106]
	Authors	Fiona Chamley	Acceleration of CE practices in manufacturing through the "Circular 4.0" project, which leverages digital technologies and data analysis to optimize resource use. The project also includes educational programs to train future leaders in sustainable strategies.	[107]
		José Arturo Garza-Reyes	Supply chain innovation via funded research integrating academic and industrial expertise to optimize business operations, applying Industry 4.0 technologies and CE practices to enhance sustainability and efficiency.	[108]

Table 2. *Cont.*

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference	
Academia	Authors	Integration of Industry 4.0 and the CE in supply chains, combining interdisciplinary research to enhance operations and logistics sustainability. This approach creates efficient systems and establishes benchmarks for sustainable operations.	[109]	
	Funding Sponsors	UK Research and Innovation (UKRI)	Creation of the Smart Sustainable Plastic Packaging (SSPP) challenge to fund research and innovation projects through university–industry partnerships. The initiative aims to reduce plastic waste, enhance recycling capacity in the UK, and decrease plastic packaging use across the supply chain.	[110]
		UK Research and Innovation (UKRI)	Establishment of research centers at selected universities to support CE projects in textile, chemical, metallurgical, and construction industries, focusing on reusing and recovering products after use and reducing resource consumption.	[111]
		Innovate UK	Creation of the “Circular Economy for SMEs—Innovating with the National Interdisciplinary Circular Economy Research (NICER) program”, aimed at promoting the development of CE projects in SMEs. To participate, SME owners must collaborate with one of the NICER centers in the UK to develop research projects focused on transitioning to a CE in their companies.	[112]
	Universities	University of Manchester (UM)	Development of a circular business model for electronic equipment companies, strategically connecting producers and consumers to enhance sustainability.	[113]
		University of the West of England (UWE)	Development of the Circular Economy Plan by students and faculty to promote sustainable and circular consumption within the university. The plan helps reduce carbon emissions, minimize non-essential plastic consumption, and strengthen partnerships between UWE, public organizations, companies, and other educational and research institutions.	[114]
		University of Cambridge (UC)	Creation of the Circular Economy Center to establish a network of organizations and academic partners, promoting research projects and scientific events. The Center provides guidance to government agencies, companies, and professionals transitioning from a linear to a circular model, offering training and mentoring.	[115]

Table 1 highlights the active engagement of academia, government, and organizations in CE initiatives. The government’s role stands out, while the collaboration and alignment between academia and organizations further strengthen these efforts.

4.2. China

China ranks second in the index developed in this study, holding fifth place in scientific publications and leading in patent registrations. It was also the first country to regulate the CE through the Circular Economy Promotion Law (CEPL), enacted in 2008. The CEPL establishes guidelines for the shared economy, prohibits the import of specific solid waste, and promotes new business models tied to emerging products. Chinese organizations excelling in the CE primarily focus on recycling and reuse, resource management and efficiency, and emission reduction. Operating across various sectors—including chemicals and materials, information technology, paper and pulp, automotive, energy, electronics, and fashion and apparel—these organizations develop longer-lasting and more recyclable

materials, implement food tracking systems to minimize waste, and launch employee awareness initiatives to support sustainable development.

In the academic field, research funding supports the development of interdisciplinary strategies and advanced tools for CE implementation. Additionally, institutes have been established to promote and disseminate CE principles among workers. This multidisciplinary approach has played a key role in advancing sustainable practices nationwide. This study identified 22 strategies and actions led by China to foster CE development, categorizing them based on government, organizations, and academic contributions.

According to Table 3, the Chinese government, organizations, and academia are developing significant initiatives to boost the CE. This reinforces international collaborations, including influential researchers participating in the IPCC and working with the UN.

Table 3. CE's Technical–Scientific Scenario (TSS) in China.

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference	
Organizations	Government	Regulation of the Circular Economy Promotion Law (LPEC)	Promoting digital solutions in emerging circular business opportunities by integrating the product design phase with innovative business models to enhance value chains.	[116]
			Regulation of the shared economy to enhance resource efficiency and expand job opportunities.	[117]
			Enactment of laws prohibiting the import of solid waste, such as plastic and paper, to minimize domestic waste generation.	[118]
	Patents	China Petroleum	Development of a method to produce a material resistant to aging while remaining recyclable at the end of its useful life. This approach prevents secondary pollution by reintegrating the material into the production cycle, supporting the advancement of the CE.	[119]
		Nchian Holdings	Implementation of systems in food companies to provide customers with transparent information on the temperature and storage conditions of products from production to shelf, reducing the risk of quality deterioration.	[120]
		Anhui Heiji	Development of technology to reduce paper fiber loss. This innovation aims to minimize the loss of fine fibers in the paper manufacturing process by increasing their surface roughness, thereby improving the physical and chemical properties of the fibers.	[121]
	Startups	Huadu Worldwide Transmission	Offering discounts to customers who exchange old auto parts for new ones at the time of purchase, thereby promoting the reuse of products and raw materials.	[122]
		GemChina	Development and implementation of technologies enabling the complete recycling of batteries, recovering valuable components from discarded units.	[123]
		YCloset	Development of clothing rental services to reduce impulsive purchases by allowing customers to experience rented clothing. This service supports the transition from a LE to a CE, increasing the reuse of clothing and accessories.	[27,124]
GRIIs	Lenovo	Creation of strategies to maximize the use of recycled plastics throughout the production process.	[125]	
	BYD	Adoption of goals for energy savings and emissions reduction, development of green and environmentally friendly products, and fostering employee awareness of sustainable development.	[126]	

Table 3. Cont.

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference
Academia	Articles	Proposition of a rigorous scientific framework for the CE concept. This paper aims to fill the academic and conceptual gaps surrounding the CE by identifying six critical challenges related to thermodynamics and system boundaries that must be addressed for the CE to contribute to global sustainability effectively. The study serves as a roadmap for researchers and policymakers seeking to enhance the real-world impact of the CE on sustainability.	[60,63]
		A 10R typology is proposed to unify various approaches to value retention in CE products and materials. The paper examines the historical development of the CE, arguing that, despite controversies and confusion, significant levels of circularity have already been achieved globally in areas such as recycling and energy recovery. The study concludes that the focus should shift toward realizing shorter value-retention options, such as remanufacturing and refurbishment, to optimize the systemic benefits of the CE.	[71]
		Development of two robust tools for implementing the CE: a database of CE strategies and implementation case studies. These tools compile 45 CE strategies applicable to different stages of the value chain and more than 100 case studies, categorized by scope and level of implementation.	[56]
	Authors	Sergio Ugliati Studies on the CE have been developed, focusing on sustainability and environmental economics, particularly emphasizing energy. His research integrates multiple disciplines, including life cycle assessment and sustainable development. His most recent work, conducted between 2017 and 2021, has concentrated on ecology, sustainability, and agriculture.	[127]
		Yong Geng Creation of the Intergovernmental Panel on Climate Change (IPCC) and acting as a consultant for UN organizations and Chinese local governments.	[128]
		Syed Abdul Rehman Khan Development of innovation projects focused on supply chain management, awarded twice consecutively by the Education Department of the Shaanxi Provincial Government, China; Dr. Syed Abdul Rehman Khan is an authority on Supply Chain Management and Logistics. He gives lectures as a guest lecturer on various topics that encompass the CE.	[129]
	Funding Sponsors	National Natural Science Foundation of China (NNSFC) Funding for projects that develop interdisciplinary platforms on bio-based materials implemented in economic sectors and evaluation of the performance of bio-composites and bamboo structures.	[130]
		Fundamental Research Funds for the Central Universities (FRFCU) Fostering research in the CE through funding that supports graduate students and PhD graduates.	[131]
	Universities	Beijing Normal University (BNU) Creation of international forums on ecology and the environment aimed at establishing sustainable objectives in environmental safety and preventing and mitigating air pollution.	[132]
		Tsinghua University (TU) Establishing international partnerships to develop projects to reduce the carbon footprint (CF) and make the most polluting supply chains less environmentally harmful.	[133]
		Shanghai Jiao Tong University (SJTU) Creation of research institutes to identify best practices, incubate innovative ideas, and train workers in CE practices.	[134]

4.3. United States

The United States ranks third in this study's proposed index, fourth in scientific publications, and second in patent registrations. The US government encourages collaboration between government, industry, and citizens, prioritizing reuse and recycling practices.

Additionally, the CE is supported through municipal, state, and federal laws, including public education and awareness actions.

The selected American organizations contribute to the CE primarily in areas such as recycling, waste technology and logistics, food and agriculture, water management, sustainable packaging, and emission-reduction technologies. They are also developing alternatives using natural by-products for product development and creating new businesses focused on technologies to reduce waste and assist vulnerable populations.

In the academic sector, institutions and authors create innovative frameworks and taxonomies, develop emerging technologies for sustainable management, and design sustainable business models. This study identified 22 strategies and actions implemented by the United States to advance CE development in the country (Table 4).

Table 4. CE's Technical–Scientific Scenario (TSS) in the United States.

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference
Government	Law 1 (federal): No Time To Waste: A Circular Economy Strategy for Wind Energy	The Office of Energy Efficiency and Renewable Energy is developing strategies to enable the CE to generate wind power electricity. To this end, processes for recovering, reusing, and recycling wind turbine blades are being created with the support of academia and industry. The glass fibers found in wind turbine blades can be recovered and repurposed in the automotive, marine, and aerospace industries.	[135]
	Law 2 (municipal): Shop Zero Waste	City authorities have launched an initiative to encourage people to choose recycled, second-hand, or repaired products as gifts rather than new ones. As a result, an online platform has been made available to the public to help users find companies that sell these products or offer repair services.	[136]
	Law 3 (state): California Circular Economy and Plastic Pollution Reduction Act	A law requires plastic packaging producers, retailers, and wholesalers to implement waste management programs to increase the recycling rate. The legislation also allows companies to form associations to develop joint waste collection and recycling actions.	[137]
Organizations	Circular economy for plastic waste to polyethylene via refinery crude unit	Development of a process that selects residual plastics and converts them into oil and/or wax using a pyrolysis reactor. This procedure ensures that polyethylene polymers achieve the same quality as virgin materials, unlike mechanical processing alone.	[138]
	Recycling of superabsorbent polymer via UV irradiation in flow system	Using UV radiation, a method has been created for degrading superabsorbent polymers present in hygiene products, such as feminine pads and diapers for babies and older people. In this way, the products are decomposed more economically, allowing them to be reinserted as raw material in production again.	[139]
	Method for preparing α -cellulose, spinning composition, and fiber material	Researchers developed a technique to treat coffee waste by decolorizing the grounds and transforming them into white powder. This process prevents the disposal of organic material in landfills and conserves natural resources for the paper industry.	[140]

Table 4. Cont.

TH and Object of Analysis	Topic	Identified Strategies and Actions	Reference
Organizations	Startups	Recyclops Selective collection systems have been developed in areas that do not have them through an application that allows truck drivers to be registered and paid for the collection and transportation of waste. This way, drivers receive collection routes and destinations to partner recycling centers.	[141]
		Scrappy & Scraps Recycling eggshells from restaurants and hotels so that these shells can be used as input in the production of dog food, making it more nutritious and functional for pets' health.	[142]
		Goodr The company provides food through reverse logistics, collecting surplus edible items from stores and delivering them to people facing food insecurity. It monitors surplus food points and plans distribution to those in need using digital technologies.	[143]
	GRIs	American Water The provision of wastewater supply and treatment services will extend the average renewal cycle of water pipes to 135 years.	[144]
		Mc Cormick Develop more sustainable packaging for the organization's products, fully replace plastic packaging, and recover the industrial waste generated.	[145]
		Cisco System The "No Paint Project" aims to eliminate oil-based wet paints on plastic products, leading to cost savings, reduced CO ₂ emissions, and the elimination of hazardous organic compounds.	[146]
Academia	Articles	Proposal of a framework that integrates circular business models and supply chain management for sustainable development, focusing on closing, slowing, intensifying, narrowing, and dematerializing cycles. Each of these categories addresses different aspects of sustainability, from waste minimization to energy efficiency.	[40]
		Development of a taxonomy of circular indicators (C-indicators) to assess, improve, and monitor CE performance. Based on a systematic review of the literature and 55 existing sets of indicators, this taxonomy is structured into 10 categories. The action aims to facilitate the selection of appropriate indicators for different levels and sectors, providing a practical tool for decision-makers in their transition to more sustainable practices.	[147]
		Integration of the CE and Big Data through a conceptual framework. This work introduces an integrative model that improves understanding of the CE–Big Data nexus. It also offers a relational matrix that clarifies the complexity of large-scale data management and stakeholders. Thus, it enables the development of a research agenda that directs studies with the integration of the CE and Big Data.	[148]
	Authors	Joseph Sarkis Developing a strong research foundation in CE and supply chain management, widely cited and recognized in academia, Joseph Sarkis has contributed to advancing knowledge with over 500 publications and leads the Circular Economy Working Group at Future Earth Systems. His research offers key insights that support academics and practitioners in transitioning industrial systems to more sustainable models, shaping policy and practice on a global scale.	[149]
		Callie W. Babbitt Developing a predictive model for electronic waste management to analyze the life cycle of electronic products and their subsequent waste. This model helps companies and governments plan for CE objectives, such as green design, reuse markets, and material recovery technologies.	[150,151]
		Mark Esposito Developing predictive models of the Fourth Industrial Revolution to support the creation of futuristic strategies that increase the efficiency and sustainability of industrial processes.	[152]

Table 4. Cont.

TH and Object of Analysis		Topic	Identified Strategies and Actions	Reference
Academia	Funding Sponsors	National Science Foundation	Creation of the project “Collaborative Research: Convergence around the CE” to award research scholarships focused on developing strategies to reduce consumption, replace materials, extend the life cycle of products, build a blockchain for tracking assets and materials, and create business models that increase the CE.	[153]
	Universities	Rochester Institute of Technology	The development of the project “Prediction of electronic waste flows for effective planning of the CE” aimed to apply the theory of industrial ecology to electronic waste through modeling methods that identify patterns in the life cycle of such equipment.	[151]
		Yale University	The university created the “Center for Industrial Ecology,” which develops research such as implementing industrial ecology in developing countries, reusing non-hazardous industrial waste, analyzing the environmental implications of emerging technologies, and creating dynamic frameworks for modeling systems that recycle fibers.	[154]
		Worcester Polytechnic Institute	Development of the “Circular Economy and Data Analytics Engineering Research for Sustainability” project to train postgraduate students in chemical and data sciences with a focus on sustainability.	[155]

As shown in Table 3, the government, organizations, and academia collaborate to promote the CE in the United States. Additionally, government initiatives range from municipal to federal levels, making them more comprehensive and capable of addressing the specific needs of each level.

5. Proposition and Discussion of a Framework for CE Development

This section analyzes and systematizes key technical and scientific information on the CE from the three countries highlighted in this study—the United Kingdom, China, and the United States. It culminates in the proposition of a framework based on the TH model designed to support the development and management of the CE. This framework includes recommendations to reduce waste and maximize resource value, fostering the transition to a more circular and sustainable economy.

The discussion of these recommendations is organized into the subsections Government (Section 5.1), Organizations (Section 5.2), and Academia (Section 5.3). This structure facilitates the identification of key aspects; the potential impacts on each TH entity; and, most importantly, the interactions between these sectors in CE development (Table 5).

Table 5. Recommendations for implementing CE based on the Triple Helix model.

TH Sector	Recommendation	Sources
 Government	Creation of legislation and environmental targets according to regional characteristics (R1)	[54,93]
	Structuring and improving inspection and adjustments in taxation (R2)	[156]
	Establishment of public–private partnerships (R3)	[95]
	Fostering innovation to develop sustainable circular business models (R4)	[95]
	Encouraging the shared economy for resource optimization and job creation (R5)	[122,124]
	Development and updating of legislation to improve solid waste management aligned with the CE (R6)	[94,137]
	Stimulus for the use of renewable energy and conscious consumption (R7)	[135,136]

Table 5. Cont.

TH Sector	Recommendation	Sources
 Organizations	Implementation of sustainable logistics for the valorization and redistribution of food and organic waste (R8)	[140,142,143]
	Integrate technological innovations and advanced chemistry practices from design to product manufacturing (R9)	[96,99,138,139]
	Extend the lifespan of products by incorporating recyclable and aging-resistant materials into their composition (R10)	[122,124]
	Implementation of technologies in organizations to improve water quality and reduce its costs, as well as effluents (R11)	[97,144]
	Encouraging green innovation for packaging and products through the implementation of circular design and reusable, recyclable, or compostable materials (R12)	[101,103,145]
	Implementation of digital solutions and real-time information collection to enhance supply chain efficiency (R13)	[120,141]
	Promoting product reuse through digital platforms and business initiatives (R14)	[100,104]
 Academia	Establishment of environmental goals and implementation of sustainable management practices aligned with international standards (R15)	[102,126,146]
	Developing frameworks to integrate I4.0 technologies with the CE (R16)	[40,107–109,148,155]
	Develop strategies and advanced circular business models to overcome barriers in B2B companies and foster collaborative networks (R17)	[105,106,113,115,129,133,149,150,153]
	Creation of CE metrics (R18)	[36,147]
	Developing solutions to improve waste management (R19)	[111,150,151]
	Integration of academic research with public policies for CE development (R20)	[114,128,130,132,149]
	Development of methodologies to improve sectoral circularity implementation (R21)	[60,63,71,113,127]

5.1. Government

The government sector plays a vital role in the transition to the CE, acting as a legislative, regulatory, and supervisory authority at various levels. The concentration of decision-making authority in the federal executive branch can vary depending on each country [156]. Specifically, in the case of China, one of the countries selected for this study, a high concentration is evident in the control exercised by the federal executive over all levels of government and social organizations, reflecting a centralized governance model [157]. In contrast, the United Kingdom and the United States share considerable power with regional and/or local governments, granting them greater autonomy [158]. Despite these differences, regardless of governance structure and the level of centralization, government strategies and actions are fundamental and should be prioritized to drive the transition to the CE. This study presents recommendations applicable at federal and regional levels in countries beyond those examined in this research.

The initiative “Creation of legislation and environmental targets according to regional characteristics” (R1) is proposed to promote environmental sustainability and circularity. This initiative should emerge from collaboration among governments, organizations, and society to enhance supply chain efficiency and significantly reduce natural resource waste. Two initiatives from the United Kingdom illustrate how to develop such laws. The first involves legislation aimed at reducing the use of disposable plastics, minimizing dependence on single-use plastic products, and encouraging their prolonged use. The second is the establishment of extended producer responsibility, requiring manufacturers to take greater accountability for the environmental impact of their products throughout their life cycle—from sustainable design to recycling and final disposal, effectively ensuring a “cradle-to-grave” approach [156,159].

The strategy “Structuring and improving inspection and adjustments in taxation” (R2) aims to discourage environments with inadequate environmental management practices. To achieve this goal, governments must gradually develop and implement actions targeting

the transformation of key economic sectors, such as the packaging industry, retail, and the consumer-goods supply chain. These actions may include offering incentives for sustainable practices and imposing penalties, such as higher taxes, on companies that fail to adopt measures like incorporating recyclable plastics into their production processes, thereby aligning them with the CE principles [111,158,159].

To accelerate the transition toward the CE, the strategy “Establishment of public–private partnerships” (R3) highlights the importance of alliances among the public, private, and academic sectors, ranging from the efficient use of resources to encouraging the implementation of advanced technologies in environmental management. These cross-sector collaborations are essential for integrating knowledge, resources, and strategies to drive innovation in products, services, and processes that meet the environmental demands of the 21st century. For example, governments can leverage these partnerships to promote urban mining and the extraction of precious metals from discarded items. In addition to environmental benefits, urban mining can create jobs and foster local development, offering workforce training opportunities in materials engineering, recycling, and logistics [95,160,161].

The recommendation “Fostering innovation and collaboration to drive sustainable circular business models” (R4) emphasizes the integration of digital solutions in the transition to circularity. For example, AI can predict demand for recyclable products and optimize waste collection routes, while the IoT can enable real-time monitoring of product life cycles [162,163].

The recommendation “Encouraging the shared economy for resource optimization and job creation” (R5) focuses on the efficient use of materials and assets, such as workspaces, equipment, vehicles, clothing, temporary accommodations, electric vehicles, and recreational equipment, all contributing to the regeneration of natural systems. A successful initiative that exemplifies this recommendation is the “BlaBlaCar” app. Initially created for carpooling, particularly on routes with limited public transportation options, this app allows car owners to “sell” seats in their vehicles to other passengers, making trips more sustainable [64,164].

The recommendation “Development and updating of legislation to improve solid waste management aligned with the CE” (R6) supports the creation of regulatory frameworks that analyze product life cycles and reduce environmental impacts from design to disposal. In France, the “National Pact on Plastic Packaging” was introduced, requiring manufacturers and distributors to incorporate at least 60% recyclable plastic into their products, showcasing a strong commitment to sustainability [165].

Finally, the recommendation “Stimulus for the use of renewable energy and conscious consumption” (R7) encourages more sustainable energy and resource management practices. This approach advocates using environmentally sustainable materials in renewable energy production. For instance, replacing steel and concrete with lighter, more durable materials like carbon fiber and polyethylene helps enhance the sustainability of energy infrastructures [135]. Clean energy infrastructure projects require both public and private funding. The African Development Bank plays a key role in developing renewable energy across Africa, serving as a model with financial policies that support the sustainable energy transition [166]. As investments in sustainable energy sources require substantial capital, companies must find solutions to ensure a return on this investment. In this context, blockchain-based technology can enhance security and efficiency in energy distribution systems, aiding in energy monitoring and helping to combat electricity theft through unauthorized transmission [167]. In the context of conscious consumption, the development of online platforms for municipalities can facilitate citizens’ access to recycled products [168]. Another example of collaborative consumption is Japan’s umbrella rental system, implemented during heavy rain events to enhance resource efficiency. However,

for these measures to be effective in society, it is crucial to assess their long-term financial viability [169].

5.2. Organization

Organizations, ranging from micro-enterprises to large multinational corporations, are crucial in transitioning to the CE. These actors are key in reshaping business practices and driving circular innovation. Large companies, in particular, contribute significantly by leveraging their vast resources and extensive reach across supply chains to drive substantial changes and establish international standards for sustainable practices [170]. Meanwhile, small and medium-sized enterprises (SMEs) are crucial in the CE transition as they form most of the business landscape and act as catalysts for local innovation. The interaction between different types of companies fosters the innovation and collaboration ecosystem needed to address the challenges of the circular transition [171]. For the development of this article, patents, sustainability reports, and activities carried out by startups in the United Kingdom, China, and the United States—spanning both small businesses and large corporations—were analyzed. It is worth noting that the recommendations in this subsection are specific and do not necessarily interact with each other. Unlike the guidelines for governments, business demands face the challenge of adapting to their characteristics and needs.

To reinforce sustainable practices in organizations, the strategy “Implementation of sustainable logistics for the valorization and redistribution of food and organic waste” (R8) can enhance the sustainable development of the food sector. Similar practices can also develop other equally sustainability-committed sectors. This initiative involves adopting CE concepts and practices in closed-loop food supply chains (CFSCs). In this context, food is classified into “usable products”, often discarded for aesthetic reasons despite being edible, and “recoverable products”, which are unsafe for consumption but sound for composting, bioenergy, or animal feed. Thus, CFSCs maximize the value of each resource, promoting their sustainable and efficient use.

Additionally, adopting the Decentralized Food Waste Management System (DFWM), which includes decentralized composting, anaerobic digestion, and biogas utilization, is recommended. This system helps reduce waste while increasing biogas production. In the construction sector, there is potential to transform specific food wastes, such as grapes, hazelnuts, and wheat, into building and insulation materials, encouraging organizations to explore these innovations for more efficient and sustainable waste management [172,173].

In the pursuit of sustainable and circular business models, the recommendation “Integrate technological innovations and advanced chemistry practices from design to product manufacturing” (R9) aims to extend the lifespan of plastics and polymer materials. This approach must implement innovative technologies in plastic reverse logistics to address challenges such as inadequate recycling infrastructure and public awareness of proper disposal and reuse. An effective strategy is to prioritize easily recyclable and biodegradable plastics, especially in critical contexts such as healthcare. Simultaneously, advancements in Dynamic Covalent Chemistry (DCC) reveal new possibilities for polymer reuse, enabling their recycling without property loss and ensuring environmentally safe decomposition. Thus, organizations, academic institutions, and industrial sectors must increase investments in research and development. Such investments drive the development of more sustainable technologies and practices related to plastics and polymers, contributing to a future where material circularity becomes an integral part of everyday life [170,174].

The recommendation “Extend the lifespan of products by incorporating recyclable and aging-resistant materials into their composition” (R10) emphasizes the relevance of circularity in product design. This approach encourages selecting materials that can be

recovered, reused, recycled, and composted. The “Design for X” (DFX) methodology is fundamental in this process as it aims to eliminate design deficiencies, minimize risks, optimize material selection, and enhance user satisfaction. By incorporating principles such as durability, modularity, ease of disassembly, reparability, reuse, and recyclability, DFX adds value for consumers and minimizes adverse environmental impacts [171].

The recommendation “Implementation of technologies in organizations to improve water quality and reduce its costs, as well as effluents” (R11) highlights the relevance of Nature-Based Solutions (NBSs). NBSs, such as artificial wetlands for filtration, rainwater harvesting, and green roofs, can significantly improve water and effluent management, contributing to environmental sustainability and cost reduction. When integrated into operations, these practices improve water quality and transform work environments by promoting biodiversity and well-being. In this scenario, reverse osmosis technology can be an effective alternative for treating surface water, balancing environmental benefits with economic costs despite a high initial investment. For irrigation, chlorinated treated groundwater is more recommended. Water resource managers must be aware of the critical aspects of this management, such as the risk of resource depletion and salinization [175,176].

The recommendation “Encouraging green innovation for packaging and products through the implementation of circular design and reusable, recyclable, or compostable materials” (R12) highlights the importance of circular design for environmentally efficient packaging. This approach involves using less complex recyclable, reusable, or compostable materials. Sustainable product examples, such as the automotive industry’s innovation in remanufacturing components like electric vehicle batteries, illustrate how collaboration between manufacturers and suppliers can optimize supply chains and improve circular efficiency. These exemplary practices should inspire other sectors to adopt similar initiatives to enhance sustainability and circularity in their operations [177,178].

The recommendation “Implementation of digital solutions and real-time information collection to enhance supply chain efficiency” (R13) emphasizes the need for organizations to adopt advancements from Industry 4.0, such as Big Data (BD) and Artificial Intelligence (AI). These technologies enable the analysis of vast data volumes, improving demand forecasting accuracy, optimizing delivery routes, and enhancing energy efficiency. Sensors and predictive analysis systems become essential for the preventive maintenance of operational structures, significantly reducing costs and environmental impacts. Intelligent energy management systems and cloud-based collaborative platforms for stakeholder information sharing further strengthen operational efficiency and support sustainable organizational development. In the construction sector, Material Passports (MPs) play a key role in managing information related to recyclability and sustainability, optimizing resource use, and promoting circular and sustainable practices in operations [179].

The strategy “Promoting product reuse through digital platforms and business initiatives” (R14) encourages conscious consumption and emphasizes the critical role of companies in aligning their practices with economic and environmental sustainability. Adopting approaches like the Closed-Loop Hybrid Business Model (CLHBM), which prioritizes material reuse and upcycling while keeping products within a continuous product life cycle, is recommended. This model embraces sustainable design principles, seeking to minimize component use and favor recyclable materials, thus generating sustainable value for businesses and the environment. Organizations must also engage stakeholders and local communities in recycling initiatives, promoting social justice and equity [180,181].

Finally, the strategy “Establishment of environmental goals and implementation of sustainable management practices aligned with international standards” (R15) underscores the importance of organizations aligning with global guidelines to promote the CE. The SMART method can help monitor critical ecological factors like gas emissions, using natural

resources, and how well recycling is carried out. Setting clear, measurable, attainable, and relevant goals aligned with environmental priorities is part of this. Establishing explicit deadlines for the execution and assessment of projects and initiatives is also important. A thorough analysis can improve resource efficiency, extend product lifespan, and encourage innovative ideas. Since sustainability and circularity are comparatively novel concepts, reskilling and upskilling initiatives are imperative for organizations to expedite the transition from an LE to a CE. Design, engineering, and manufacturing professionals often lack a sufficient understanding of sustainability principles, which makes it necessary to implement training programs to integrate CE practices into employees' daily lives [182]. Integrating "Green Skills," encompassing technical, operational, and interpersonal skills, into corporate training strategies is important for sustainability and circularity transitions. These skills increase resource efficiency, promote biodiversity conservation, mitigate climate change, and increase environmental responsibility in corporate practices [182]. Organizations must develop training modules that address the importance and management of these indicators in training programs so that it is possible to monitor employee engagement in active participation in and achievement of environmental objectives. Industry 5.0 (I5.0) is a significant concept that facilitates this recommendation by advocating workforce transformation and emphasizing sustainable, resilient, and human-centered production systems. I5.0 is an innovative framework providing workers with competencies corresponding to CE principles. This concept drives job transition and improves the conditions for companies to remain flexible with respect to the complex demands of the CE [183]. These programs should promote a sustainable and circular organizational culture, increasing employees' environmental and social responsibility. Therefore, organizations should prioritize transparency and continuous improvement, ensuring long-term adaptation to sustainability standards through workforce reskilling and training strategies prioritizing corporate environmental commitments [184]. Rigorous monitoring of these indicators reflects and consolidates a genuine commitment to sustainability as a non-negotiable corporate value [41].

5.3. Academia

The academic sector plays a significant role in the transition to the CE. It is essential in developing research that generates innovations and applied solutions. It is also important in human resource training, equipping leaders and technical professionals for the job market with specific competencies to promote circular development [12]. The propositions related to the academic sector are grounded in the realities of the three countries investigated. They encompass key elements such as scientific articles, which are essential for knowledge dissemination; the work of influential authors, many of whom are researchers and professors driving innovation; universities, which serve as research and development incubators by providing educational infrastructure for training professionals in the CE; and funding sources, including government, non-governmental, and public-private partnership agencies. These financial resources are crucial in accelerating the transition to the CE by enhancing laboratory infrastructure, offering scholarships for researchers and students, funding projects, supporting journal publications, and enabling participation in conferences, among other initiatives [20,21,82,91].

The proposal "Development of frameworks to integrate I4.0 technologies with CE" (R16) focuses on promoting the circularity of production activities. This strategy directs research towards a more sustainable sector, aligning intelligent technologies with environmental management. These frameworks should be designed to optimize resource use, establish databases that support corporate decision-making, and enhance companies' circular performance. Their development requires collaboration between academic and industry professionals to overcome barriers and bridge the gap between theory and practice. This

synergy fosters innovation in supply chains and strengthens circularity, accelerating the development of sustainable solutions and increasing the market viability of innovations [185]. In this sense, I5.0 can contribute to developing frameworks that align technological innovation with pro-ecological strategies and are oriented towards professional development [186]. I5.0 can enhance the digitalization of the supply chain and facilitate real-time monitoring to optimize material reuse and recycling [187]. In the realm of personal development, I5.0 can be employed to amalgamate automation and AI within corporate universities to enhance creativity and equilibrium in decision-making [181,188]. Therefore, these frameworks focus on areas such as production, where structured models guide the adoption of emerging technologies (robotics, automation, and blockchains) to improve reuse, recycling, and resource efficiency and marketing, where experts leverage these frameworks to lead awareness campaigns on circularity, using I4.0 and I5.0 technologies to engage and educate stakeholders [189].

To transform traditional business models into ones that contribute to sustainable development, the recommendation “Develop strategies and advanced circular business models to overcome barriers in B2B companies and foster collaborative networks” (R17) is proposed. In this sense, creating specialized CE centers at universities and research institutes that integrate processes such as reverse logistics and additive manufacturing with advanced technologies is suggested. These centers are essential for minimizing resource consumption and environmental impacts through local sustainable business networks. The academic sector is crucial in formulating strategies and models that guide companies in improving their environmental performance, providing solutions for organizational agility and effective network collaboration for resource reuse and recycling [105,190,191].

The UN’s SDGs represent a global call to action in the international context of sustainable transformation. CE actions are intrinsically linked to various SDGs, such as Access to Clean Water (SDG 6), Clean Energy (SDG 7), Decent Work (SDG 8), Sustainable Consumption (SDG 12), and Terrestrial Life Preservation (SDG 15). In this context, the importance of the “Creation of CE metrics” (R18) in companies and governments to quantify and monitor progress towards circularity is emphasized, aiming to meet the established goals for each SDG. CE researchers must create circular indicators to track pollutant emissions and optimize using environmentally friendly raw materials. These indicators will guide actions to reduce emissions and enhance resource efficiency, directly contributing to SDGs related to renewable energy and water management [192–196].

The recommendation “Development of solutions to improve waste management” (R19) emphasizes integrating sustainable practices in industrial and urban environments, focusing on reuse, recycling, and minimizing waste. This proposal represents an opportunity for universities and funding sources to promote industry-oriented research to reduce packaging use and increase recycling capacity. Additionally, these institutions should encourage university research centers to promote the CE across various industrial sectors and address informality in the waste management chain by proposing studies that strengthen extended producer responsibility [111,151,153,197]. Another important aspect of avoiding waste generation is the integration of robotics with digital monitoring systems in remanufacturing. This enables improved raw material management, cost reduction, and increased energy efficiency [198]. It is worth noting that “digitalized” remanufacturing can have superior effects to recycling, taking into account the fact that it preserves resources and avoids the exploitation of raw materials [199,200].

The recommendation “Integration of academic research with public policies for CE development” (R20) highlights the importance of aligning academic initiatives with governmental guidelines. Universities should be encouraged to establish research centers and development plans dedicated to the CE, reducing carbon emissions and increasing

the use of recyclable materials. This academic–policy integration seeks to develop and implement sustainable practices in supply chain management and circular production models in industries [131,154,201,202].

Finally, the “Development of methodologies to improve sectoral circularity implementation” (R21) highlights the need to adopt innovative and collaborative practices essential for facilitating the transition from linear economic models to sustainable circular systems. Funding sources should stimulate collaboration between organizations and research centers, adapting circularity to their operations and vice versa. Universities should develop projects that integrate advanced CE systems with innovative recycling technologies through AI, the Internet of Things (IoT), and biotechnology, contributing to the sustainable development of people (social), organizations (economic), and the sustainable use of natural resources (environmental) [112,203].

5.4. Roadmap for CE Development

Government institutions play a key role in the transition to a CE. To this end, governments must establish regulatory frameworks, provide financial incentives, and ensure that national strategies are compatible with sustainability goals. While the TH framework emphasizes the interaction between government, industry, and academia, this study identifies and analyzes how government-led strategies can drive circular initiatives and foster more effective collaboration with industry and research institutions.

To illustrate the operationalization of the 21 recommendations (R1–R21) within this government-centric framework, we propose a roadmap for implementing the CE. Within this framework, government policies serve as catalysts for CE transformation, leveraging private-sector innovations and academic research to establish a systematic and iterative implementation process. This roadmap unfolds into six interconnected phases: Policy Generation from Academic Inputs, Developing Pilot Projects in Partnership with Organizations, Analyzing and Validating Academic Results, Improving and Scaling Policies, Fostering Innovation and Technology Transfer, and Global Connectivity and Replicability (Figure 5).

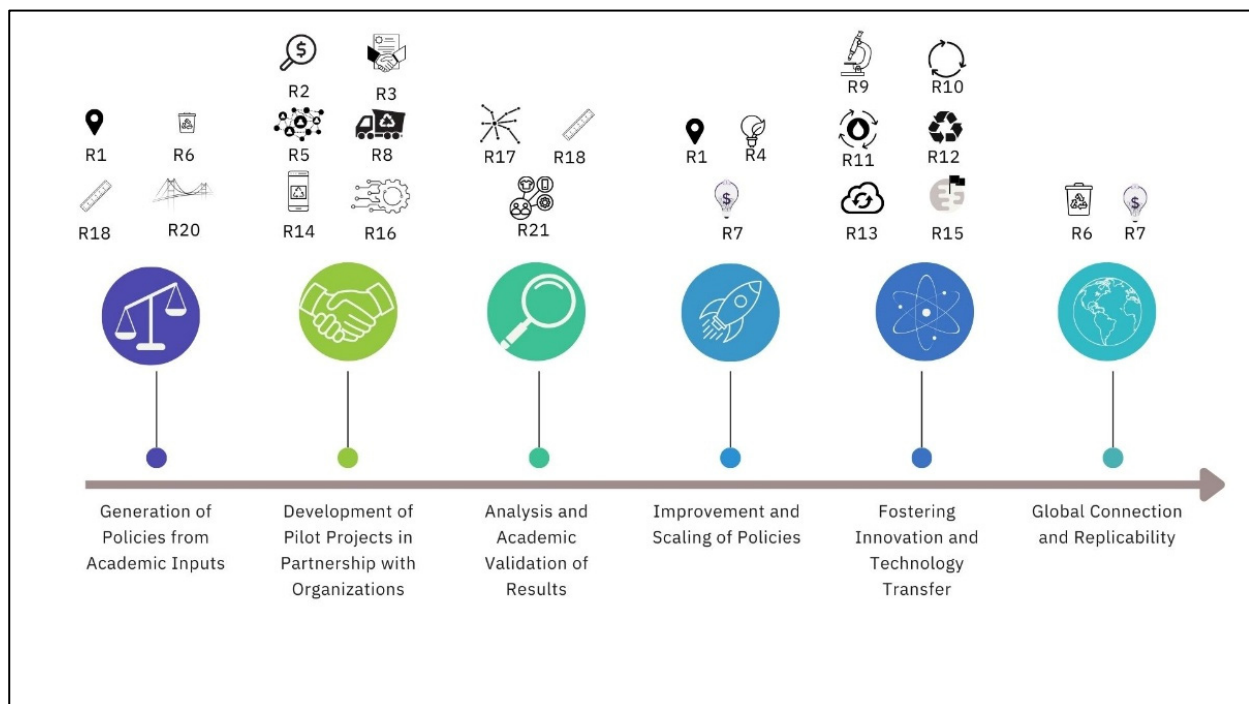


Figure 5. Roadmap for CE development.

In the first phase, policies should be generated from academic inputs (R1 and R6), drawing on research and data from universities and research centers. These institutions should analyze new technologies, assess risks, and evaluate environmental effects (R18 and R20). This process aims to support public officials in developing incentives, regulations, and sustainability requirements. The authors of [204] point out that, although scientific models have limitations, they are essential to support environmental policies, as in the case of climate change. Likewise, the CE requires regulatory actions based on research, even in the face of uncertainty. In addition, the authors of [205] show how academia influences environmental regulations, collaborating with municipal governments in the creation of standards based on scientific diagnoses, such as greenhouse gas emission protocols and resource efficiency policies.

In Phase 2, these measures should be applied to develop Pilot Projects in Partnership with Organizations. Policies such as R2, R3, R5, R8, and R14 can be tested in collaboration with organizations focusing on reverse logistics, sustainable packaging, or using Industry 4.0 technologies to improve resource efficiency. During this phase, academia (R16 and R19) should provide technical and scientific support to ensure a solid theoretical basis and real-world implementation options. In this situation, buildings like living labs can help by serving as test beds for pilot projects. This encourages open innovation and teamwork between businesses, government, and ordinary people. These ecosystems enable testing solutions in real environments, reducing risks and accelerating the adoption of circular practices [206,207].

In Phase 3, the Analysis and Academic Validation of Results should occur, where educational and research institutions (R17 and R21) are encouraged to evaluate the pilot projects rigorously. This process includes developing methodologies and indicators (R18) to assess waste reduction, efficiency, and material reuse. Among the six stages, this one should require the most effort from governments due to the difficulty in defining reliable indicators that can measure the actual impacts of circular practices. In this sense, the authors of [208] identified more than 300 indicators to monitor the CE but pointed out inconsistencies among them. The authors of [209] emphasized the importance of integrating dimensions, such as environmental (assessing emission reduction, material efficiency, and impacts on biodiversity), economic (costs and benefits of using recovery and recycling, the impact on job creation, and the viability of creating circular businesses), social (working conditions, impacts on public health, and consumer acceptance of circular products), and technical (the quality of recycled products and the efficiency of industrial and value processes) dimensions, in the analyses of material flows within the CE.

In Phase 4, Policy Improvement and Scaling occurs when the government refines rules and incentives (R1, R4, and R7). Simultaneously, organizations should scale up the methods tested in pilot projects, applying them across the entire production process. Educational institutions, such as schools and universities, must explore innovative solutions to address potential technological or financial challenges, ensuring continuous improvement of the model. The authors of [210] highlight that the expansion of successful initiatives is not automatic and requires a prior assessment of scalability, considering factors such as strategic alignment, financial viability, and compatibility with existing infrastructure. Without such an assessment, even effective small-scale policies may fail when scaled up to different sectors and contexts. In the same vein, the authors of [211] analyzed the implementation of the CE in the European Union and demonstrated that integration between government, business, and academia was essential to expand circular practices. However, they pointed out that structural barriers, such as technological adaptation costs and resistance to change, need to be overcome for the CE to become a dominant economic model.

Once the initiatives' effectiveness has been demonstrated, the Promotion of Innovation and Technology Transfer (Phase 5) enables governments and specialized agencies to provide subsidies and funding to accelerate the adoption of circular practices, including patent protection and technology dissemination (R9, R11, and R13). Organizations are expected to integrate these new practices into their operations, while universities should monitor their impact, train experts, and initiate further research (R10, R12, and R15). Successful policies or projects should be replicated in other parts of society. The authors of [212] emphasize that innovation in small and medium-sized enterprises (SMEs) is essential for competitiveness and circularity. However, it depends on cooperation with universities and research centers. Furthermore, they point out that government funding and tax incentives are crucial for SMEs to overcome financial barriers and adopt circular practices. The transition to sustainable models may be unfeasible without this support, especially in less developed regions. Digitalization and Industry 4.0/5.0 in the CE, highlighting technologies such as Big Data, the IoT, AI, and blockchains as key tools for tracking material flows, can increase efficiency and reduce waste; however, companies must be able to use these technologies. When public policies do not match market incentives, this can delay the transition [213].

Successful policies or projects should be replicated in other parts of the Global Connection and Replicability phase (Phase 6). Adapting ideas that have worked in one location to suit local cultural and economic situations (as indicated in R6 and R7) is essential. This movement can create a continuous process of improvement. Each cycle is expected to refine the suggestions and usage of CE practices, promoting the ongoing involvement of the three sectors of the TH model. In this way, each recommendation integrates into a cohesive framework where the government, academia, and the private sector collaborate and coordinate efforts, ensuring that the CE evolves, consolidates, and spreads widely. Governments assume a pivotal leadership role by instituting regulatory frameworks, fostering cross-border collaborations, and offering financial incentives for circular business models. The author of [61] contends that instead of modifying conventional linear models, governments ought to proactively endorse the reconfiguration of business models to integrate circular principles. The Circular Business Model Canvas (CBMC) offers a systematic framework for policymakers and businesses to synchronize value propositions, supply chains, and revenue models with CE principles, thereby ensuring that policies promote innovation and adherence. Likewise, the authors of [214] assert that scalability is contingent upon policy interventions that promote Circular Business Model Innovation (CBMI) and mitigate obstacles for enterprises shifting to circular models. They emphasize the necessity of customized regulatory modifications that align with local infrastructure, consumer behavior, and economic circumstances, facilitating the effective implementation of successful CE strategies across various regions.

6. Conclusions

This article analyzes opportunities for and challenges to implementing the CE based on the TH model under government leadership. Thus, the CE is essential to postponing Earth Overshoot Day and mitigating pressures on Planetary Boundaries. Collaboration between government, organizations, and academia is indispensable for creating public policies on circular innovations, which will contribute to sustainable development. This work achieved its objective by proposing a framework based on the TH model for government, business, and academic sectors to implement CE elements under government leadership.

To ensure the effectiveness of the research, this work was developed in five steps. In Step 1, we established the fundamental elements of the study by identifying a scientific gap, formulating a research question, and defining objectives. Moving forward, Step 2

meticulously selected and classified the countries for analysis by specifying search parameters in scientific databases and applying criteria such as the H-Index and patents. Subsequently, Step 3 mapped the Technical–Scientific Scenario of the CE by collecting data from government websites, companies, and research institutes and interpreting these documents through the lens of the TH model. Based on this, Step 4 processed the information obtained and systematized the main findings, highlighting innovations and initiatives in the three countries analyzed. Finally, in Step 5, we recommended and discussed a TH model framework by presenting recommendations, integrating findings into a broader context through a roadmap, and answering the initial research question.

Furthermore, the study explored how governments can integrate the TH sectors to create public policies that support circular practices and promote coordination among government, organizations, and academia. By analyzing best practices within each TH sphere, both individually and collectively, and systematizing recommendations for circularity, the study addressed the scientific gap identified in the introduction regarding the role of governments in promoting the CE.

This study contributes to the CE and TH literature by including different perspectives and systematizing successful practices in various countries, enriching the understanding of the cross-sectoral dynamics necessary for an effective transition to the CE. As an applied contribution, the proposed framework offers practical guidelines that help TH sectors support CE development. Recommendations include creating specific legislation, encouraging the shared economy, promoting public–private partnerships, and providing a viable roadmap for governments to lead the transition to a more sustainable economy.

This study also serves as a reference for organizations and academia, highlighting their respective roles in promoting circularity. Future research should deepen the analysis of interactions between TH sectors in specific contexts, such as different regions or industries. Additionally, investigating the impact of emerging technologies, such as Artificial Intelligence and the Internet of Things, on implementing CE practices may reveal new scientific and market opportunities and challenges. It is also suggested that indicators be developed to evaluate CE progress across various scenarios, enabling the monitoring and adjustment of adopted policies and practices.

From another perspective, we encourage research that seeks to align policies at the international level in a way that promotes cross-border collaborations in circular initiatives. We also propose conducting studies that identify the influence of financial mechanisms, such as green bonds and sustainability-linked loans, as a strategy to accelerate the adoption of the CE. Another promising avenue for research is the development of business models that integrate I5.0 principles (with a focus on human beings, resilience, and sustainability) within the CE framework.

Author Contributions: Conceptualization, M.E.; methodology, M.E. and J.S.d.M.R.; validation, M.E. and O.J.d.O.; investigation, M.E.; resources, M.E. and O.J.d.O.; writing—original draft preparation, M.E., J.S.d.M.R., E.C.B.G. and A.C.F.C.; writing—review and editing, M.E., A.B.T.R. and C.F.P.; project administration, O.J.d.O.; funding acquisition, M.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) [314918/2023-0] and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A Detailed Description of the Research Method

In this appendix, each of the 14 research stages, which are contained in the five steps, are described in detail (Table A1).

Table A1. Detailed methodological flow.

Stage (A–N)	
Step 1—Defining the basic elements of the work	A—Definition of the theme
	B—Identifying the scientific gap
	C—Elaborating the research question
	D—Establishing the research objectives
	E—Choosing the scientific method
Step 2—Establishing criteria for selecting units of analysis	F—Definition of search parameters
	G—Ranking of countries to collect information and data
Step 3—Mapping the Technical–Scientific Scenario	H—Collection of information and data from selected countries
	I—Critical interpretation of selected documents
Step 4—Data treatment and systematization of the main findings	J—Exploration of information from technical and scientific documents from the three countries chosen to compose the Technical–Scientific Scenario
	K—Systematization of information about the CE in the technical–scientific literature by country
Step 5—Presentation and discussion of results and conclusions	L—Framework proposal for CE development based on the Triple Helix model
	M—Discussion of results
	N—Answer to the research question

In Step 1 (defining the basic elements of the work), after choosing the study topic (Stage A), a literature review and content analysis were conducted to interpret textual data from articles related to the CE. This approach enabled the discovery of existing materials on the topic, identifying scientific gaps to be explored (Stage B). This process culminated in the formulation of the research question (Stage C) and the definition of the research objectives (Stage D) [81,82]. Finally, the TSS-based IR method for the CE (Stage E) was selected based on its ability to provide a comprehensive and multidimensional topic analysis. Unlike traditional literature reviews, this approach integrates diverse sources of information—such as academic publications, patents, government policies, corporate sustainability reports, and startup innovations—to provide a holistic view of CE developments. By organizing and analyzing this data in a planned way, the method not only helps us better understand the current state of the CE but also helps build a framework that fits the Triple Helix (TH) model. This ensures that we have a complete picture that includes contributions from government, business, and academia [83].

Step 2 (establishing criteria for selecting units of analysis) was divided into two main stages: defining the search parameters in scientific and technical databases (Stage F) and ranking countries for data and information collection (Stage G). In Stage F, search and selection parameters were applied on Scopus for scientific data and Lens for technical data due to their extensive collections of articles and patents on the CE. These platforms provide citation metrics and encompass a significant volume of available materials, surpassing other databases in this field [20,84,85]. In Scopus, works in English were selected, as it is the most influential and impactful language in academia [81]. The advanced search filter used for article selection was as follows: “Circular Economy” in the title; document type:

“article” or “review”; source: “journals”; publication year from 2016 to 2021; written in English; excluding publications from 2015.

Patents considered in the development of the technical scenario were selected using the Lens database in May 2021 with the descriptor “Circular Economy”, resulting in 208 patents. Additionally, the same filter was applied on the Corporate Knights website [87] to gather data from companies’ GRI reports. In Stage G, documents retrieved from the databases were analyzed to rank the three most representative countries in terms of the CE. This ranking was based on the relationship between two criteria: the H-Index and the number of registered patents. The H-Index quantifies the impact and relevance of scientific research, serving as a bibliometric metric that assesses the academic productivity of countries, universities, and authors, among other entities [86]. Initially, the 16 countries with the highest H-Index scores and the 16 countries with the most registered patents were ranked, as shown in Figure 3. The shaded countries were those that had participation in both rankings. It is important to note that, in cases of ties in the H-Index or the number of patents, countries were assigned the same rank. Subsequently, countries that appeared in both columns were identified, resulting in the Final Ranking, which was composed of the average positions between the H-Index and patent variables.

#	Country	Patents	#	Country	H-Index	#	Country	Patent Position	H-Index Position	Total
1	China	1069	1	United Kingdom	40	1	United Kingdom	3	1	2
2	United States	157	2	Italy	34	2	China	1	5	3
3	United Kingdom	32	3	Netherlands	31	3	United States	2	4	3
4	Canada	24	4	United States	29	4	Italy	8	2	5
5	Japan	20	5	China	28	5	Netherlands	13	3	8
6	Taiwan	19	6	Spain	26	6	Spain	12	6	9
7	Australia	17	7	Sweden	25	7	Canada	4	16	10
8	Italy	16	8	Germany	24	7	Brazil	10	10	10
9	Belgium	15	8	France	24	7	France	12	8	10
10	Brazil	14	9	Denmark	23	8	Australia	7	14	10.5
11	South Korea	13	10	Brazil	22	9	Belgium	9	13	11
12	Spain	8	11	India	20	9	Germany	14	8	11
12	France	8	12	Finland	19	10	Sweden	16	7	11.5
13	Netherlands	7	13	Belgium	17	11	Portugal	16	16	16
14	Germany	6	14	Australia	16					
15	Russia	5	15	Poland	14					
16	Mexico	4	15	Switzerland	14					
16	Portugal	4	16	Portugal	12					
16	Sweden	4	16	Austria	12					
16	Singapore	4	16	Canada	12					

$$\text{Final Position Index} = \frac{\text{H-Index Position} + \text{Patents Position}}{2}$$

Figure A1. Ranking of countries.

In this index, the lower the average between the variables, the better the country’s position, as illustrated in the Final Position Index in Figure A1. It was observed that the leading countries had the highest H-Index scores. Based on these criteria, the selected countries were the United Kingdom, China, and the United States.

In Step 3 (mapping the Technical–Scientific Scenario), after selecting the countries, the process of mapping the CE’s TSS began. Initially, data were collected for each country (Stage H) by consulting various sources, such as government websites, funding agencies, universities, and reports from leading companies. The goal of this stage was to identify relevant technical and scientific information to advance the research topic. After excluding documents not applicable to the research objective, the remaining data were critically analyzed and interpreted (Stage I) from the TH perspective.

Step 4 (data treatment and systematization of the main findings) involved exploring information from technical and scientific documents from the three selected countries to compose the CE TSS (Stage J). Subsequently, a content analysis of these documents was conducted to systematize the main innovations and government, industrial, and

academic initiatives from the mapped countries within the CE TSS through the TH model perspective (Stage K). Developing the TSS involved identifying and analyzing elements such as contributions from major universities and authors, relevant studies, government efforts and policies, industrial initiatives, patents and innovations, and GRIs [20,83,91]. Official documents, such as reports from national and international agencies, government pages, and countries with the highest numbers of CE-related patents, were analyzed. The analysis and systematization of this information, combined with the author's expertise, supported the formulation of the framework. This framework aims to contribute to joint initiatives between the public and private sectors, driving not only the advancement of the CE but also broader societal progress [82].

In Step 5 (presentation and discussion of the results and conclusions), a framework was developed and proposed, structured around the TH model (Stage L), as illustrated in Figure 4. The recommendations suggested in the framework were thoroughly presented and discussed (Stage M), highlighting the importance of contributions from organizations, governments, and academia for the advancement and effective management of the CE. In this phase, the research question of the study was also answered, integrating the findings into the broader research context (Stage N).

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