Asia Pacific Academy of Science Pte. Ltd.

Sustainable Social Development 2026, 4(3), 8539.
https: //doi.org/10.23812/ssd8539

Article

Historical evolution and financial challenges of circular economy and closed-loop systems

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CITATION

Challoumis, C, Eriotis N, Vasiliou D. Historical evolution and financial challenges of circular economy and closed-loop systems. Sustainable Social Development 2026, 4(3), 8539. https: //doi.org/10.23812/ssd8539

ARTICLE INFO

Received: 3 April 2026
Revised: 11 May 2026
Accepted: 18 May 2026
Available online: 28 May 2026

Abstract: The current research seeks to study the evolution and financial problems faced by circular economies and closed-loop systems from a sustainability perspective. In terms of the scope of this research, it will focus on discussing the transition to circular economies from traditional approaches to economics and the financial and environmental problems associated with such a change. As for the goals pursued by conducting this research, it can be said that the primary goal will be understanding the contribution made by circular economies to the process of sustainability and discussing important financial factors preventing the implementation of these ideas. At the same time, it can be stated that the current research paper uses a theoretical approach, based on a detailed literature review and historical analysis. The use of this methodology makes it possible to consider the economic, financial, technological, and environmental aspects of the problem in question and combine them in one system to gain a more thorough understanding of it. Despite their well-documented benefits, circular economy and closed-loop systems continue to face significant financial challenges. Case studies—such as Omega-3 production from waste fish oil, biodiesel from used cooking oil, and eco-industrial parks—demonstrate both their viability and economic potential. However, these examples also highlight that high investment costs and financial risks remain key barriers to large-scale adoption.

Keywords: circular economy, closed loop systems, social ecosystem, sustainable development

1. Introduction

The contemporary interpretation of a Circular Economy (CE) is based on an economic system that generates no waste and pollution, keeps products and materials in progress, and promotes the NK cycle of production, distribution, and consumption. The CE concept represents a transition from a linear pattern toward a non-linear position in which resource inputs and waste, emission, and energy leakage are minimized by slowing loops, closing loops, and narrowing loops; therefore, these three strategies act as the fundamental principles of CE [1–16]. CE addresses the indefinite maintenance of the economic, natural, and social ecosystem by optimizing resource and energy efficiency through clean production and closed-loop manufacturing, while simultaneously pursuing the reduction or elimination of waste. A system that reuses resources is resilient and better able to handle shocks and disturbances. What systems are more likely to provide these benefits? Sewell et al. answer: Several principles are foundational for creating circular systems. First: Begin with the concept of a resource rather than a product. Second: Make use of feedback flows; resources must circulate and not be lost or disposed of to the environment. Third: Maintain a system that supports resource flows; if the system collapses, resource circulation stops. Resilience literature widely finds that systems that recycle, reuse, or remanufacture resources are more resilient and better able to cope with turbulent conditions. Hence, resources should be preserved and retained to preserve system resilience. Therefore, the defining feature of a circular is flow [17–27]. The CE is a concept that has gained considerable attention among researchers and policymakers, widely regarded as a key driver for achieving sustainability. At its core, CE represents a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the traditional linear economic model, CE aims to decouple economic growth from the consumption of finite resources through the development of a restorative circular system. A closed-loop or circular economy proposes to gradually decouple economic growth from the consumption of finite resources through the development of a restorative circular system. A circular economy encompasses different business models that replace the "end-of-life" concept with reducing, reusing, recycling, and recovering materials in production/distribution and consumption processes. The approach distinguishes between technical and biological cycles [4,28–45]. According to Mason et al., a circular economy should be restorative and regenerative by design, enabling product materials to flow easily through value chains. Governments, companies, and citizens play a crucial role in facilitating this transition.

Three dimensions to shifting from a linear to a circular society, where materials are kept in loops at their highest utility. Designing linear products and systems using circular economy principles fosters flourishing, resilient, and regenerative assets. The key components of a circular economy are resource recovery, circular supplies, and product life extension. Resource recovery involves capturing and cycling discarded materials, components, and by-products back into the economy, thereby reducing poor resource access and price volatility. Circular supplies replace scarce or non-renewable resources with renewable, recyclable, or biodegradable materials, forming the foundation for continuous resource circulation. Product life extension keeps products, components, and materials at their highest utility and value through strategies such as designing for durability, reuse, remanufacturing, and refurbishment to avoid premature disposal. Resource recovery from waste is an essential component in both closed-loop and circular economic systems, which aim to keep resources in use longer and contribute to sustainable development [46–60]. This subsection defines resource recovery and compares its contribution to sustainability within linear, circular, and closed-loop flow systems. A circular economy seeks to decouple economic growth from finite resource extraction by encouraging reuse, repair, remanufacture, and recycling, thereby extending product life and maintaining the value of materials. Closed-loop systems companies have further committed to eliminating waste by designing products and processes to continuously reuse energy and materials at either the nanoscale or macroscale, effectively creating circular flows within and between sectors. Interconnected with design for longevity and waste minimization, resource recovery thus provides the backbone to closed-loop progress.

A circular economy is an alternative conceptual framework for sustainability that seeks to reconcile the economy with finite planetary boundaries. Linear, open-ended consumption models dominate global economic systems, characterized by linear flow dynamics and disconnected operation. By contrast, the circular economy is a closed-loop system that employs interconnection at all scales as a foundation for resilience and addresses all sustainability facets in principle. The circular model encourages perpetual circulation through iterative reuse, repair, remanufacture, and recycling, eliminating waste and pollution, reducing resource extraction, and limiting the scope of the technically irrecoverable, thereby theoretically preventing resource depletion and environmental harm. Resource recovery plays an essential role in making these objectives achievable. Design for longevity is recognized as a key component of circular economy thinking that has the potential to reduce environmental impact and create value through the extension of useful product and material life. Extending the lifecycle of products and components is important in minimizing demand for finite materials and the energy used to process them. Product life extension strategies and techniques may also increase opportunities for the creation of ‘slow-moving stocks. Such ‘slow-moving stocks’ refer to a tendency to retain material and product stocks for an extended period,” most of which are unlikely to be recovered or returned to the production cycle for long periods [61–70]. Waste minimization is defined by the European Commission as a principle of pollution prevention prioritizing the reduction of waste generation and the re-use of materials over other waste management techniques that recover waste or dispose of it in an environmentally safe manner. Waste should be recirculated to production and consumption processes. Zero waste means no waste is wasted under the circular economy system. The transition from a linear to a circular economic model is illustrated in **Figure 1**.

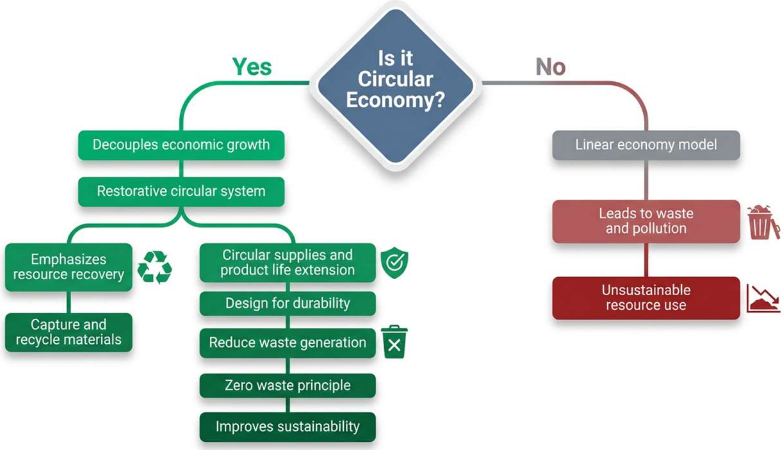

Figure 1. Circular economy (authors’ scheme).

Figure 1 presents the crossroads of the linear take–make–consume–dispose economy and the emerging CE. It becomes critical to investigate the current approaches to Circular Business Models (CBMs) and their diffusion among firms. Delivering products as services helps firms to maintain closer contact with customers and better manage valuable materials while providing consumers access to certain products that can be used on demand without financial burdens. The concept of a circular economy represents a major transformation of the current, predominantly linear economy in which resource use is decoupled from economic growth, the two forms of capital (natural and man-made) are regarded as complementary, and humanity operates in a sustainable manner within terrestrial boundaries [71,72]. It offers the potential to generate multiple benefits, both linked directly to the operation of CE systems, such as lowered demand and depletion of natural resources, and indirect benefits such as reduced pollution and improved human health through the elimination of environmental externalities. Additional benefits include a reduced need for waste management by landfill or incineration, economic growth, increased employment and welfare, reduced material price volatility, and improved trade balances. The successful, broad-based adoption of CE typically requires the transformation of existing linear supply chains into closed-loop networks where end-of-life (EoL) products are recovered, reused, and remanufactured. Transforming industries and companies from traditional to circular supply chain networks requires the development of logistics networks aligned with product design requirements [6,12,13,73–80]. Another important consideration includes the implementation of collecting and recovering procedures, as well as the use of remanufacturing centers in the design of such networks. The developed conceptual framework allows for designing the closed-loop supply chain network efficiently. In order to increase the clarity of analysis, this paper will be presented as a conceptual study, focusing on the role of finance-related issues in the transition toward circular economy models. Although many scholarly studies discuss technological, environmental, and legal aspects of circular economies, the issue of finance, including the role that financial markets can play in the shift towards circular economy, still lacks theoretical attention. Hence, this study will investigate how financial factors can affect the rate of circular economy adoption and development. The core question of this study will be related not to proving that circular economy is beneficial but rather to explaining how financial barriers impact the possibility of developing such systems compared to others.

2. Materials and methods

The current research employs theoretical and conceptual methodology, which is based on the thorough analysis of the existing literature and the historical development of the concepts of the circular economy and closed-loop systems. Unlike other research designs, which are based on the use of primary data and statistical tests, this research relies on the integration of theoretical frameworks related to the discussed topics. Methodology is based on comparative theoretical analysis, where the shift from linear models of economics ("take-make-dispose") to circular models is studied [81]. The main concepts underlying such a shift are analyzed through the literature review to create a common theoretical framework for research. Resource circulation, systems' resilience, loop slowing, loop narrowing, and loop closing are just some of the concepts that will be considered. Such an approach allows us to determine the differences between linear and circular systems structurally [7,9–11,14,15,45,82–84].

Furthermore, the paper adopts the historical-analytical approach, analyzing the historical emergence of ideas associated with the circular economy from early notions such as industrial ecology and cradle-to-cradle design to modern-day political and technical implementations [85,86]. The diachronic view allows detecting both continuity and change in the development of theoretical conceptions, which reveals how the circular economy paradigm has developed into a holistic socio-economic theory. Moreover, the research approach includes the application of the theory of systems thinking, which considers the economy to be a network of systems, wherein materials and energy flow. In particular, the analysis of closed-loop systems, which involve feedback and recycling in the production process, is done by recognizing that this approach is able to reduce waste and increase resource efficiency [11,14–16,45,68,83]. Lastly, the research employs conceptual modeling. In this case, the fundamental concepts of the circular economy, including resource recovery, extending the life span of products, and circular supply chains, are modeled in such a way that they become an integral part of an analyzable framework. This method allows for the generalization of the theory and serves as the basis for further testing. Thus, the methodology is interpretive and explanatory, meaning that the research is conducted to generate theories and not to validate hypotheses statistically.

The literature review process involved adopting an interpretive methodology for organizing the literature, which aimed at transparency and consistency in selecting and analyzing relevant sources. Literature inclusion criteria considered studies that dealt with resource flows, sustainability transitions, funding issues, and systems models, excluding mere descriptive accounts of the issues without any critical analysis. The literature synthesis method involved comparative analysis, where the points of convergence and divergence between different studies were highlighted and clustered around thematic areas. Despite not using any specific literature coding software, a method of organizing the literature based on iterative classifications along key dimensions (environmental, technical, regulatory, financial, and socio-cultural) was adopted. In order to improve the validity of the explanatory power of the theoretical framework, the current research relies on empirical examples drawn from case studies and secondary statistical results found in the literature. Examples of applications include the use of waste fish oil in producing Omega-3 products, the manufacturing of biodiesel from used cooking oil, and the practice of industrial symbiosis in eco-industrial parks. Furthermore, some of the metrics that can be employed to bolster theoretical claims include cost disparities between virgin and secondary raw materials, investments required to implement reverse logistics, and the uptake of circular business models. Even though the study does not collect its own data or conduct any econometric analysis, incorporating empirical references strengthens the theoretical outcomes.

3. Environmental benefits

The circular economy is a socio-economic system that aims to maximize the circulation of materials within economic systems through resource-efficient use of products, components, and materials in both technical and biological cycles. This regenerative approach supports the delivery of society’s needs with considerably less fresh material consumption. As a consequence, the circular economy can contribute substantially to the achievement of long-term global environmental objectives. These include harmonizing human activities with the planet’s ecological boundaries, safeguarding life-support systems, controlling sea-level rise and ocean acidification, protecting ecosystems and biodiversity, and reducing direct and indirect pollution of the air, land, and water. By mitigating these environmental pressures, the circular economy also addresses significant risks such as resource scarcity and dependency, economic instability, international conflicts, and geopolitical tensions. The fundamental concept of a closed-loop system has been embedded in environmental policy for many years, relying on an integrated approach that views the materials lifecycle as a collective whole [2,46,87–96]. Closed-loop systems reduce pressure on the environment through the efficient use of resources, ensuring that as much value as possible remains within the system and that all outputs can be viable inputs for other processes, either within the same system or elsewhere. This systematic perspective necessitates closed-loop thinking across design, production, supply, consumption, reuse, and end-of-life management. Furthermore, the establishment of closed-loop systems yields a more resilient and stable society.

Such systems move away from dependence on competitive pricing and instead secure costly but essential resources such as land, energy, and capital by maintaining a steady flow of materials and products within the system. Economic benefits constituted an important pillar for the circular economy and resource circulation. Huge employment and value generation opportunities through the circular economy for materials, products, components, and their transportation were expected with a focus on large sectors such as manufacturing, automotive, construction, food, and electronics, and small- to medium-sized enterprises. In dominating the EU economy, the manufacturing and construction sectors constituted great potential for the circular economy transition. The circular economy and the related closed-loop material-sector networks emerged as the sustainable alternative to the contemporary economic and industrial model, aiming to prevent waste generation and avoid excessive and wasteful resource extractions. Participants from public, private, and academic sectors and NGOs expressed their convictions that the circular economy was part of the solution for a sustainable 21st-century economic system. Social benefits seemed to be of particular interest to participants when discussing the circular economy as the next economic model. Because the circular economy was depicted as a path to sustainability in the future, the transition was expected to generate social benefits in terms of human development. Increased quality of life, increased innovation, reduced unemployment, job-creation potential, and improved health and well-being were all clearly identified by more than one stakeholder [7–11,14–16,45,68,76,83,84]. In addition to environmental and economic benefits, the circular economy offers a variety of social advantages, which can be explained in terms of the following three factors. First, for low-income households, a circular economy promotes the use of high-quality second-hand goods, reducing outlays for new products and thereby helping to alleviate poverty. Second, because circular economy activities tend to be more labor-intensive than the corresponding linear economy activities, they create additional employment and associated social benefits. Third, as highlighted in the textile sector, the circular economy offers considerable educational benefits and promotes desirable lifestyle changes, thereby indirectly providing cultural benefits to society at large [2,87–94].

Through these factors, the circular economy system has the potential to create a prosperous society in a fair and just manner. A number of challenges still hinder a large-scale transition from the prevailing linear setup towards a more circular model, which may facilitate resource-intensive development with fewer materials. Major constraints on implementing the circular economy and moving from a linear to a closed-loop supply chain include technology, regulations, policies, and societal/cultural factors. Tackling these obstacles requires additional research and entrepreneurial development of new sustainable business models; reverse supply chains must incorporate sorting processes before product recovery to enhance end-of-life value. The circular economy spans multiple scientific fields—such as renewable energy and storage, industrial ecology, and bioscience—and addresses issues related to limited material and energy resources as well as environmental degradation. Realizing its benefits demands system-wide change in practice and behavior across industrial sectors and society, considerable effort in policy development, alongside expert input from a range of disciplines. The key environmental dimensions and their contributions to sustainability are summarized in **Table 1**.

Table 1. Environmental benefits of the circular economy and closed-loop systems (authors' table).

Dimension	Environmental benefit	Explanation	Impact on sustainability
Resource efficiency	Reduced consumption of raw materials	Circular systems reuse, repair, and recycle materials, minimizing the need for virgin resource extraction.	Preserves natural capital and reduces resource depletion
Waste reduction	Minimization of waste generation	Closed-loop processes transform waste into inputs for new production cycles.	Decreases landfill use and environmental contamination
Pollution control	Reduction of air, water, and soil pollution	Lower emissions due to efficient production and recycling processes	Improves environmental quality and public health
Climate change mitigation	Lower greenhouse gas emissions	Reduced energy use and material extraction decrease the carbon footprint	Contributes to climate stability and global warming reduction
Ecosystem protection	Preservation of biodiversity and ecosystems	Reduced extraction and pollution protect natural habitats	Maintains ecological balance and life-support systems
Resource circulation	Continuous flow of materials within the economy	Materials remain in use for longer periods through reuse and remanufacturing	Enhances system resilience and sustainability
Energy efficiency	Lower energy consumption	Recycling and remanufacturing often require less energy than primary production	Supports sustainable energy use and reduces emissions
Reduction of Externalities	Internalization of environmental costs	Circular models reduce negative environmental spillovers	Promotes environmentally responsible economic activity
Water conservation	Reduced water usage in production	Efficient processes and recycling decrease water demand	Supports sustainable water resource management
Land use optimization	Decreased pressure on landfills and extraction sites	Reduced waste and resource extraction lower land degradation	Protects land resources and reduces habitat destruction

The analysis provided in **Table 1** shows that the environmental benefits of the circular economy are not merely stand-alone gains but represent an overall systemic shift in production and consumption behaviors. Through efficient use of resources, waste reduction, and pollution prevention in tandem, the circular economy helps protect natural capital while also improving ecosystem resilience. This set of benefits is interdependent, as less raw material extraction requires less energy, which results in fewer emissions and environmental destruction. In addition, the continual reuse of materials enhances the robustness of economic systems by decreasing their reliance on finite resources and external shocks to their supply chains. Nevertheless, the environmental benefits cannot be gained without the proper adoption of enabling technologies, policies, and social change. Thus, even though the circular economy presents a holistic approach to attaining environmental sustainability, it needs to be accompanied by joint efforts from all sectors of society.

4. Technological barriers

Closed-loop systems aim to establish enduring cycles involving materials, components, and products, thereby limiting the necessity for additional material extraction while reducing raw material losses and waste generation within manufacturing and consumption processes. The successful operation of such systems hinges on the deployment of appropriate technological capabilities for the design, manufacturing, and operation of assets within the synchronous flow of materials. In transitioning from linear to circular systems, several technological barriers warrant consideration. Industries with established installation capacities and mature production processes perceive the reengineering of such systems as resource-intensive and inherently risky, thus exhibiting resistance to adoption. Furthermore, the current quality of outputs from innovative manufacturing technologies, such as additive manufacturing, may not align with the rigorous standards required for substituting conventionally manufactured products, posing an additional impediment. Public acceptance also constitutes a critical hurdle; products fabricated from recycled materials often confront skepticism in markets characterized by risk aversion and deep-rooted perceptions of quality and reliability [9,15,16,45,84,97]. The maturity of a production value chain closely correlates with the magnitude of these technological barriers. Consequently, sectors such as plastics, textiles, paper and pulp, and metals—each exhibiting considerable maturity—encounter the most pronounced obstacles in adopting circular economy-enabling technologies.

5. Regulatory issues

Extended Producer Responsibility (EPR) is a widely applied policy approach within the circular economy paradigm. It assigns producers financial and organizational responsibility for their products’ end-of-life management, with the objective of incentivizing design for resource efficiency, increased product durability and repairability, and improved recycling and reuse rates. EPR schemes have been applied in various sectors – including packaging, electrical and electronic equipment, batteries, vehicles, construction, and textiles – in a range of policy domains ranging from economic instruments to product standards and guidelines [98,99]. Species of EPR obligations include initiatives on recycled content mandates, sectoral bans such as restrictions on single-use plastics, material bans, taxes on material extraction to ensure product traceability, and packaging taxes or levies. Moreover, EPR is often embedded within extended value-chain initiatives that consider the entire product lifecycle, involving suppliers, distributors, and consumers. Despite the wide variety of implementations, EPR remains limited in scope, both in terms of policy design and regulatory extent. EPR reforms require a focused and comprehensive regulatory strategy, as well as the implementation of innovative enforcement instruments. Additionally, effective monitoring and evaluation of EPR schemes necessitates a set of indicators and metrics tailored to specific material flows, products, and organizational units. A comprehensive redesign of existing frameworks is therefore imperative to overcome the challenges posed by contemporary circular economy objectives. Even in strongly circular nations, cultural resistance comprises a major barrier to circular consumption [2,46,87–96,100–103,]. Social values represent much deeper obstacles than lack of knowledge, especially for behaviors evoking guilt or discomfort or requiring time and inconvenience to change. Individuals, families, and entire countries may favor disposing of still-usable products to allow the appearance of out-with-the-old-in-with-the-new, which particular companies promote. Yet the poverty or population crises motivating circularity in countries like Bangladesh and Portugal demonstrate cultural values to be malleable.

Circular economy refers to an economic and industrial system that is restorative and regenerative by design, aimed at reducing global resource consumption and minimizing material leakage. It stands in contrast to the linear or 'take-make-dispose' model, which dominates the current system and is largely responsible for many growing environmental concerns. Several guiding principles characterize such a system. A circular economy aims to keep materials in use for as long as possible. The first principle expects the system to seek and maintain a state of balance or equilibrium, ensuring consistency for continued human activity as well as for natural material flows and ecological systems. Availability of renewable resources is a prerequisite for system functioning and, therefore, any programs designed within such a system should be able to operate without a continuous need for non-renewable or unconventional resources. The system must be designed such that the accumulation of material from both human society and from external sources does not occur. If the material in the system increases by accumulation, the system will eventually lose stability and self-regulation capability, and suddenly shift to a different state. Finally, if there is a material increase in one part of the system, it must be balanced by an equal reduction elsewhere. If the input material enters an artificial system, the cycling material that leaves the system should either be returned to the biosphere without harm or be reused in the technological cycle. These three principles relate to resource circulation, system resilience, and continuous and balanced flow of materials. The following sections discuss the circular economy concept in more detail, examining the principles and associated terms to illustrate the potential benefits arising from implementation. Many well-established businesses have already adopted closed-loop circular economy processes. The increasing use of digitally connected products paves the way for the circular economy while enabling companies to collect crucial information about how products are used and maintained. A study of large, well-referenced companies reveals that the most popular circular economy practices involve durable product design, interchangeability of parts, maintenance, repair and reuse, product life extension, multifaceted resource recovery as output, intermediate differentiation, and product lifespan extension. Collaboration with innovative startups that develop novel technologies for CEOs (e.g., CRM), as well as adopting incremental innovations from established market players (Advanced Manufacturing and Digital Circular Processes), supports the transition. Diversifying asset and product functionality contributes to meeting economic objectives by creating differentiated intermediate outputs or services and leveraging company assets. Ecosystem diversity influences performance within B2B closed-loop circular supply chains [2,4,30,44,46,90,96,101–106]. Closed-loop supply chains address a wide range of value creation activities, presenting key challenges mainly related to manufacturing, product return management, and cost control. Circular supply chains expand the traditional objective of efficient return to the original supplier to encompass new market opportunities.

Although CE is currently enjoying newfound popularity, many of these ideas date back at least until the 1960's if not earlier; hence, a wide range of insights and experience are available to support emerging global CE initiatives. For example, analysis of closed-loop supply chain (CLSC) development, closer upstream/downstream integration, and RESTOR (recovery, extension, and sale or reuse of returned materials) frameworks provides a rich source of lessons to enable CE schemes to avoid pitfalls and accelerate progress. Other broad lessons, relevant laws, regulatory ideas, best practices, and sector-specific examples are likely to be explored in later work. Technology plays a central role in enabling circular economy implementation and accelerating the transition to closed-loop supply chains. Digital technologies facilitate real-time tracking of materials and waste flows, allowing better linkages between supply and demand. Data-processing platforms use real-time Internet of Things (IoT) sensor inputs or historical data to continuously monitor and optimize manufacturing, logistics, and remanufacturing processes. Digital twins of products, processes, or entire systems enable advanced scenario modelling and decision support for longer product lifetimes and increased circularity.

Machine learning automates and adapts process optimization given changing conditions within the circulation system. By combining Process Intensification—a strategy for maximizing transfer processes within production stages—with Additive Manufacturing, AI for real-time decision-making, and microreactors, resource efficiency can be maximized and waste reduced. Big Data analytics and cloud computing support more accurate forecasts of supply, demand, and prices, reducing imbalances that lead to waste generation. Linking digital product passports with extended producer responsibility systems can increase reuse and the circulation of materials across the supply chain. IoT tagging and tracking of unique items improve management and prevention of e-waste and agricultural waste, helping organizations capture additional value from resource flows. On the materials side, advances in chemical recycling, micro recycling, bio-based polymers, and biorefineries enable the remanufacturing, recycling, and extraction of materials from waste streams. By doing so, the lifetimes of primary materials and products are extended, and the environmental impact of down-cycled secondary materials is lowered. At the product level, new sorting technologies (e.g., hyperspectral imaging and AI), enhanced design methods, advanced materials, and coatings facilitate easier disassembly and reuse of components and materials. Additionally, innovations such as distributed manufacturing can reduce inventory requirements by enabling local and on-demand production of spare parts and components, supporting circular economy adoption by reducing material losses and enhancing supply chain resilience [1,89,107–111]. The interaction between regulatory instruments and circular economy outcomes is illustrated in **Figure 2**.

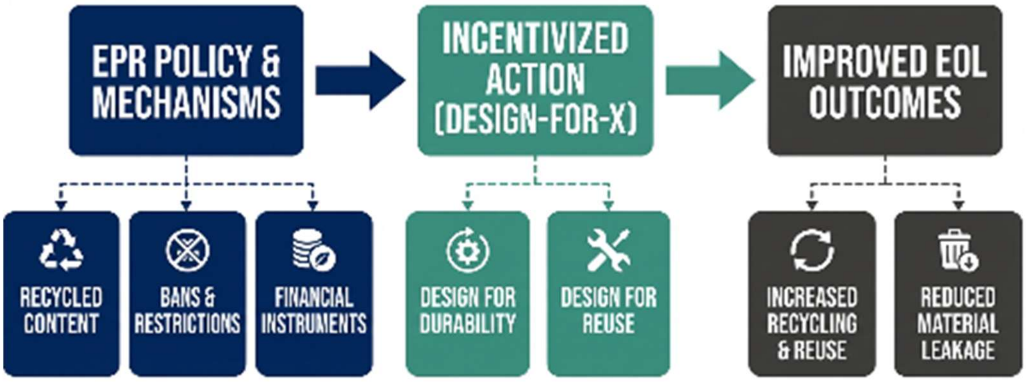

Figure 2. Circular economy (authors' scheme).

Figure 2 provides a visual depiction of the causal link between regulations, incentive-based actions, and EoL results under circular economy. In this case, extended producer responsibility (EPR) and other such regulatory measures like recycled content mandates, restrictions, and financial tools serve as primary incentives which influence company actions. The policy levers generate incentives for organizations to engage in design-for-x practices, especially design for durability and design for reuse. Consequently, better EoL results are realized in terms of more recycling and reuse activities as well as minimized material losses. Hence, the diagram is useful in highlighting how an effective policy response, complemented by design-oriented initiatives, can positively impact material flow under circular economic conditions.

6. Digital tools and platforms

Digital tools and platforms support information-sharing and, by increasing transparency, encourage better choices throughout supply chains and in the circular economy implementation process. Digital transport forecasts can help optimize logistics and reduce resource use and emissions. Online platforms can support the repair and reuse of products or wider asset-sharing. Blockchain technology can provide an audit trail to improve personal security and verify provenance and authenticity. Digital technologies also release innovative business models such as pay-per-use systems, sharing platforms, and product-as-service activities that help the circular economy transition [5,9,84,112–119]. Data management supports both ecosystem and social integration by unlocking the full potential of data and making it available to citizens and different players along value chains in an open and transparent manner. Innovative Materials. The design or incorporation of innovative materials can allow for circular economy systems to establish themselves. In particular, sustainable binders used in cement and concrete can improve the circularity of the cement system, beyond reducing CO_2 emissions during production. However, current challenges include the lack of regulatory guidelines, limits on production capacity and supply of raw materials, and a lack of knowledge and communicative materials. Digital innovations, such as smartphone applications that promote the circular economy, can help address these limitations. The app provides information on Local Self Government (LSG)-associated plastic waste recycling management, remedial measures for plastic waste management, guidelines for color coding and segregation of plastic waste at source, and details of Common Plastic Waste Collection Points (CPWCPs). Indeed, consumer measures can be as effective in promoting circular economy principles as those introduced at the industry [4,6–9,11–16,30,44,45,68,76,82–84,104,120]. The circular economy supports the decoupling of economic production and consumption from finite resource inputs and waste accumulation through closed-loop interactions of biological and technical cycles.

Strategies for the optimal use of biological materials include cascade recycling and the elimination of hazardous substances to facilitate leakage from technical cycling, whereas technical loops require increased efficiency, enhanced circularity, and the management of scarce elements. Digital technologies, including product life-cycle monitoring, data tracking, and smart materials, enhance measurement and profit-optimization and facilitate optimal material use, but widespread implementation of large-scale circular processes remains limited. Business models such as access and performance, extension, and sharing models link circular design to longer service life and traverse private and public spaces, while state-of-the-art tools such as Life Cycle Assessment support circularity assessment. China applies the circular economy concept throughout industrial production via a top-down policy approach, and integrated manufacturing and industrial symbiosis within an eco-industrial park context serve as a platform for circular economy realization. The CE contributes to the process of decarbonization and the transition to the Renewable Energy Society, but biophysical constraints and physical boundaries of resource circulation restrict material flow so remain fundamental considerations. The CE literature offers limited coverage of the continued dependence on primary materials, and circular water management has received little attention.

7. Manufacturing

In developing environmentally sustainable production systems, manufacturing organizations play a central role, since manufacturing activities generate most of the economic wealth worldwide. The manufacturing sector is a major resource consumer and a major contributor to environmental pollution. It essentially provides the built environment of today’s societies – i.e., the durable artefacts and infrastructure that provide the comfort and convenience demanded by modern life – as well as the essential interrelated products and services. Products manufactured today have long service lifetimes and are thus the dominant economic stocks of the society in which they circulate [6–9,11–16,45,68,76,82–84,120]. The public demand for new and different products, fast technological innovation, and the material abundance of the contemporary world have resulted in an historically unprecedented level of materials throughput in recent decades. This unforeseen speed-up of the consumption of natural resources is now largely recognized as being unsustainable and essentially competes with meeting basic human needs. The pressures on the natural environment are such that, without reconsidering current practices, it will be impossible to grow the global economy and, at the same time, reduce the environmental impact of the production sector.

8. Construction

The construction industry requires about 30% of all extracted raw materials worldwide on an annual level, which makes the implementation of the Circular Economy concept (CE) in the sector both important and challenging. Backflows (flows of products, components, materials, or waste from downstream to upstream stages in the supply chain) are of primary importance in this respect. This research is discussed in the light of reverse-logistics management, models of material accumulation in buildings, and the supply analyses of critical raw materials, which argue that in the industrial world, most materials are nevertheless still accumulating in products, buildings, or stockpiles at any one point in time. This fact complicates the material flow between stages in forward supply chains and explains in part why a simple closed-loop supply chain is extremely difficult to implement in practice. The construction industry is further characterized by the dominance of fixed-product systems, and the way that materials are locked or embedded in stocks and out of circulation is even more pronounced than for many other sectors. All premises and land-sites to which a construction project applies represent a competitor for the resources needed in the project and can delay the start-up of the construction project. Therefore, it is not only the building itself that acts as a stock between two flow cycles, but practically the entire site [4,6,12,38,40,44,68,104,121]. A related intriguing feature of these premises/land-sites is that they almost always belong either to a different owner than the construction company or, in many cases, to a different legal person. At this point, it is thus evident that the construction industry should be characterized by extremely long lead times, which tend to increase the time at which flows are out of phase and thus hinder the implementation of a closed-loop system [2,87–89,91,94,104–106,111,121–127].

9. Agriculture and textiles

Circular agriculture applies the circular-economy concept to food production, defining circularity largely as minimizing dependence on crude oil through the use of agricultural wastes such as straw, husks, and other residues. Many countries feature a biogas facility in circular-agriculture models, with technology addressing the combined integration of several agricultural wastes. China, recognized as the pioneer, has implemented government-led national strategies since 2013. The European Union issues comprehensive policies supporting circular agriculture. Other countries display contrasting deployment models. Peru and China prefer government-led top-down approaches; Peru integrates biogas technology to accelerate development and achieve parallel objectives of poverty reduction and emission mitigation. Italy and Germany rely on market mechanisms such as subsidies and tax credits under the umbrella of the European strategy. Technology reviews emphasize the suitability of anaerobic digestion and composting, while socio-economic analyses stress the influence of environmental and economic attitudes and of socio-demographic factors such as age and education on farmers' participation. Textiles are a significant source of waste, and the concepts of the circular economy have therefore attracted interest in this sector. A systems approach to their management avoids the externalization of social and environmental costs. Rapidly rising disposal costs triggered interest in such a paradigm shift, as textile products often end up in landfills or incinerators. The circular economy aims for a zero-waste scenario, turning waste into valuable resources. Waste is generated at all stages of the textile pipeline, from fiber, yarn, and fabric production to the end of a product's life, and both industrial and consumer waste needs to be addressed. Such principles, therefore, require a systems approach that goes beyond traditional reliance on supply chains to include the recycling and reuse of materials. This links closely with the concept of Industrial Ecology [28–34,58–60,55–57]. The paradigm extends not only to producers and distributors, but also to consumers and retailers. The latter influences the availability of new products through their choices of the market offerings, as well as the collection of garments post-consumption. Market forces impact on the transformation of waste into resources. Mechanical recycling faces a number of technical challenges relating to the trade-offs between textile properties, fiber quality, residual colors, and costs. Low-cost virgin materials also discourage the adoption of such approaches. Chemical reprocessing has therefore become the focus for the production of products across multiple industries beyond the textile sector. The European Commission-funded Resyntex project evaluates chemical processing for the four most common fiber types: Cellulosic, protein, polyester, and polyamide.

10. Policy frameworks supporting the circular economy

Policy frameworks play an increasingly central role in supporting the Circular Economy transition by motivating a wide range of private and public sector actors to contribute resources and capacities towards common sustainability goals. At the global level, international organizations such as the United Nations, the Organization for Economic Co-operation and Development, and the Ellen MacArthur Foundation have been highly influential in outlining the overall principles of circular systems and drawing attention to the role of specialized enabling measures at different scales. Internationally agreed policies on waste, resource consumption, and climate change, while falling short of a direct Circular Economy mandate, have established important interdependencies between sectors and operational levels. At the national level, governments such as China, Japan, and South Korea have developed rather elaborate Circular Economy road maps, which either fully integrate Circular Economy elements in national five-year plans or complement green growth strategies with comprehensive policy mixes. The benefits of adopting a circular economy approach might seem obvious, but many challenges remain, both technological and regulatory. Current consumer behavior is another barrier; thus, awareness and education play important roles in its success. The Circular 2.0 initiative is dedicated to promoting the circular economy as a means to improve the quality of life, the environment, and economic health. Circular 2.0 facilitates connections and partnerships, providing support to communities, entrepreneurs, operators, researchers, and others working within the circular economy framework. Social and environmental challenges are intrinsic to communitarian practices, with the perception of a closed-loop economy in re-entering material streams linked to system openness or closure [55,88,91,94–96, 105,124–127]. The transformation towards circular economic practices is analyzed by considering the degree of selective renewal of production modes. Local initiatives are categorized across four types: (1) displacement of unsustainable practices and operationalization of alternative means, (2) new interstices within existing systems and reformulation of mainstream practices, (3) new connections within alternative spaces of circulation, and (4) reconfiguration of state–citizen relations to devise appropriate new frameworks for governance.

11. Consumer behavior and circular economy

Circular economy is a transformative model that seeks to maintain the value of products and materials, minimize waste and resource use, and promote the continued reuse of resources rather than allowing them to exit the economic flow after a single life cycle. Consumer awareness and education play a crucial role in shaping behaviors that either enable or hinder the transition to a circular economy. Increasing consumer understanding about the environmental benefits of circular practices encourages the adoption of more sustainable consumption patterns. This behavior change is essential to closing the material loops that form the basis of a circular economy. Relevant knowledge and education are crucial to the transition towards a circular economy. They can help raise awareness of the circular economy and promote the implementation of circular practices and circular business models. The circular economy requires much more knowledge than the linear economy, which now furthers the linear economy and hinders the transition to a circular economy. Residents often have low levels of awareness about waste segregation, its impact, and the potential benefits it could yield for their municipality and themselves. Sustainable consumption practices necessitate the design of products with a circular economy in mind, underscoring the significance of the design stage, which determines the majority of environmental impacts throughout a product’s lifecycle. This approach promotes shared consumption, reuse, repair, remanufacturing, and recycling. Controlling the leakage of industrial materials into the environment is essential to minimize pollution [7–9,11,14–16,45,82–84]. Industrial materials that are no longer required should be safely reintegrated into the biophysical environment. The steel industry exemplifies this, where natural materials such as iron ore are extracted and processed into steel products. Maintaining a balance with ecological and cultural values is vital, with the expectation that residual materials could eventually re-enter natural biogeochemical cycles.

12. Measuring success in circular economy: Case studies

The extensive practical application of circular economy concepts has generated a multitude of accompanying knowledge and technologies, prompting the emergent concern of the concrete evaluation of circularity. As a conceptual framework, the circular economy offers broad guidelines; yet, its effectiveness is challenged by the prevailing unsustainable industrial structure and socio-economic system. Moreover, the dissemination of diverse evaluation approaches, key performance indicators, and monitoring frameworks further complicates the appraisal of circularity. Within this evolving context, the establishment and validation of monitoring systems are essential to may support their practicality and efficacy. Against this backdrop, the imperative to advance the circular economy concept and transition towards a more robust socio-economic system is highlighted. Appropriately synthesizing established knowledge and technologies calls for a comprehensive understanding of the relevant factors and conditions. In this manner, an integrated perspective facilitates the formulation of complementary monitoring guidelines that augment the operational potential of the circular economy model. Key performance indicators (KPIs) can provide insights to investors, regulators, consumers, and other stakeholders regarding the social impact of circular business models. The transition to a circular economy must be accompanied by a system that models and quantifies the impacts that sourcing and production have on society in an adequately transparent and comparable manner. Until now, the number of KPIs in relation to a circular economy indicator framework has been limited, and no principal definition has been formulated. Nevertheless, widespread circular economy implementation is a gradual process, relying on the collective efforts of governments, businesses, and society. Performance can be measured on three tiers: Impact assessment is one of the essential „enablers" in managing transformation processes to the Circular Economy. The quantification of positive and negative effects of including Circular Economy features into products and services requires the definition of Unified Key Performance Indicators (KPIs) to be able to monitor the development of Circular Economy and derive recommendations for action in product and process development, in politics, at the end users and the society for the introduction and detraction of the Circular Economy transformation. Various approaches exist for evaluating Circular Economy measures [1,87,89,106,109–111,121]. To the extent they exist, their KPI concept, the corresponding indicators, and associated assessment procedures usually do not represent all effects in a balanced way but rather focus on specific implementation areas as well as certain stakeholder groups.

The evaluation of impacts within the Circular Economy transformation is multidimensional. It is possible to consider environmental, economic, and social aspects on a national, regional, sectoral, or company level—both with regard to the production and the consumption side. The Circular Economy approach attempts to can enhance the preservation of natural capital as well as the promotion of economic and social capital. An overall evaluation system should develop measures for different dimensions, scales, and stakeholder demands and consider the assessment results in a balanced way during the decision-making process.

There are case studies for circular economy like the production of Omega-3 from waste fish oil and the development of eco-industrial parks that reduce carbon emissions and increase resource utilization [128]. Similarly, the reuse of ferrous sulfate in water treatment processes and the conversion of used cooking oil into biodiesel exemplify circularity's potential to significantly reduce carbon emissions and valorize waste streams [129]. Furthermore, initiatives such as the reprocessing of end-of-life fishing gear into high-quality consumer products like apparel and accessories, and the transformation of agricultural by-products into bio-chemicals or sustainable building materials, underscore the breadth of circular economy applications in mitigating environmental burdens and fostering sustainable production [130]. These diverse examples highlight the transformative potential of circular economy principles across various industrial sectors, moving beyond traditional linear models to create closed-loop systems that optimize resource efficiency and minimize environmental impact [131]. This comprehensive application of circular strategies is evident across the European Union, where recycling consistently emerges as a primary method for reintegrating materials into economic systems and reducing reliance on virgin raw materials, thereby fostering virtuous economic cycles [132]. The strategic integration of circular economy principles also extends to sectors like the maritime industry, where initiatives range from repurposing fish by-products for nutraceuticals and cosmetics to developing comprehensive waste management systems for fishing ports [133]. This approach, often termed the "blue economy," encompasses the sustainable use of aquatic ecosystems, extending circular economy tenets to oceans, rivers, and lakes to design out waste and pollution, regenerate natural systems, and enhance competitiveness [134]. This integration enhances economic viability by lowering costs and achieving greater economies of scale, increasingly blurring the lines between circular and blue economic models [135]. The versatility of the circular economy paradigm further extends to various industries, including the sustainable management of seafood waste and the optimization of car manufacturing processes, demonstrating its broad applicability in minimizing industrial waste and promoting resource longevity [136].

In order to give an organized depiction of the implementation of the principles of a circular economy, **Figure 3** shows a multi-industry approach to the valorization of waste and the integration of closed-loop systems. This **Figure 3** is a compilation of several industry-specific examples that show how waste products can be turned into value-added commodities. Through this diagram, one can see the transition from a linear to a circular approach to economic growth and the connections between the processes involved in both approaches.

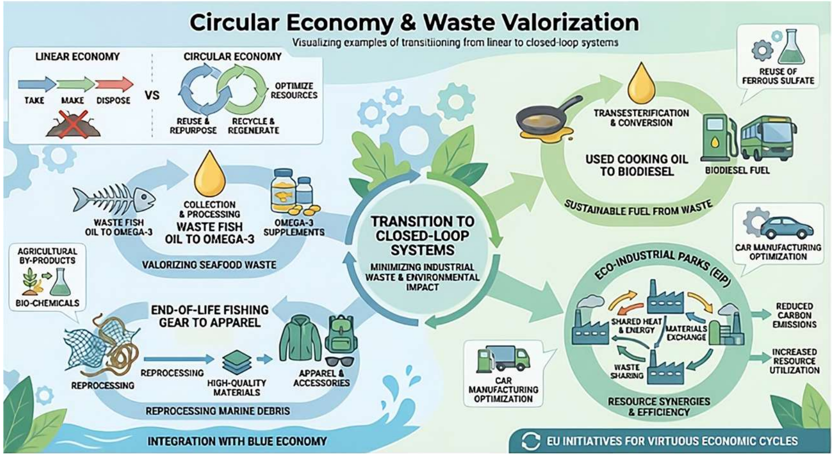

Figure 3. Cross-sectoral circular economy applications and waste valorization in closed-loop systems (authors' scheme)

Figure 3 illustrates the fact that circular economy solutions rely on interdependent resource streams that facilitate converting waste into valuable economic resources while minimizing negative effects on the environment. Examples of waste-to-product processes include the processing of waste fish oil into Omega-3 supplements, the use of used cooking oil to produce biodiesel fuel, and the reuse of industrial wastes in wastewater treatment processes. Additionally, the concept of eco-industrial parks and the adoption of circular approaches in the blue economy underscore the potential scalability of such solutions. In sum, the illustration provides an indication of the fact that circular economy relies on technology, finance, and policy mechanisms for its implementation.

In order to create a coherent view of circular economy activities in several sectors, **Figure 4** offers a conceptual model showing the interrelation between waste streams, circular economy principles, and value-added products. As seen in the **Figure 4** below, different types of waste materials, including fish processing waste, used cooking oil, production residue waste, and agricultural waste, undergo recycling and re-manufacturing processes to create value-added goods. In addition, the use of facilitating conditions such as finance, policies, technology, and cooperation shows that implementation of circular economy principles is systemic in nature.

As shown in **Figure 4**, the circular economy is an interlinked system where the generation of waste is transformed into productive output via various processes. The creation of products such as nutraceuticals, biofuels, clean water, and sustainable materials suggests the effectiveness of circular economy practices in delivering both economic value and environmental benefits. The involvement of enabling systems, especially finance, regulation, and technology, shows that successful adoption goes beyond technology itself but relies on economic and institutional factors as well. Furthermore, the listed results—namely the reduction of carbon footprint, efficient use of resources, and social benefits—indicate that circular economy solutions can support sustainability efforts if appropriately backed by relevant policies and finances.

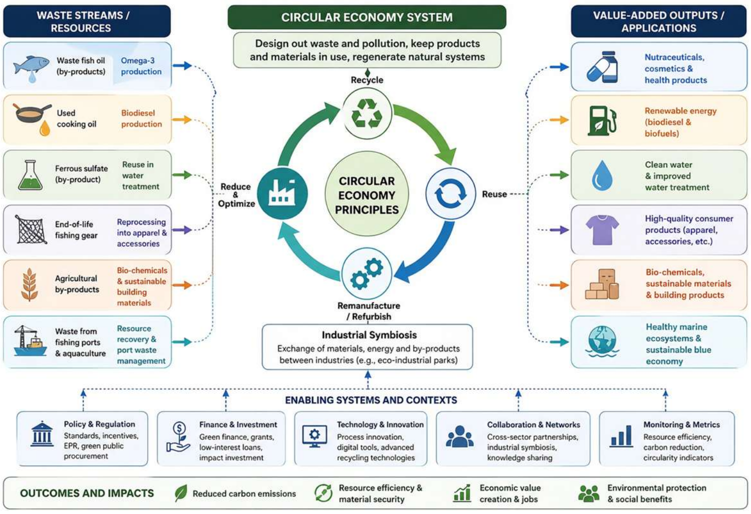

Figure 4. Conceptual heatmap of interdependencies among circular economy dimensions (authors' scheme).

13. Financial issues in the transition to a circular economy

The shift towards a circular economy involves numerous financial considerations that can impact businesses, sectors, governments, and even financial institutions. Although a circular economy offers the potential for sustainable efficiency, optimal use of resources, and innovative value generation, it presents significant financial issues in the short term, including investment, risks, and restructuring costs. It is crucial to understand the financial aspects involved in the implementation of a circular economy in order to determine its applicability and viability. Perhaps the most important financial consideration is the large investment costs required for the adoption of a circular economy strategy. Circular business models necessitate the redesign of products in ways that make them durable, reusable, and recyclable. Economic studies show that financial considerations are key influencers of the adoption of the circular economy framework. For example, the economic viability of recycling and remanufacturing processes is greatly influenced by changes in the prices of primary resources; in the case of reduced prices of virgin material, recycled material may be less economically feasible. Moreover, reverse logistics necessitates large financial investments to create necessary infrastructures, sorting technologies, and transport networks. The difficulty is most apparent among SMEs, which have restricted access to finance. Moreover, a circular business model, such as a product as a service approach, introduces an innovative way of generating profit, involving delays of cash flow generation and increased financial risks. Additionally, reverse logistics and manufacturing plants require significant investment. Businesses that operate in industries where a linear economy model is prevalent may lack the necessary liquidity to invest in such ventures or may find such investment risky [2,83]. It becomes especially acute in the case of small and medium-sized enterprises that lack opportunities to acquire funding through relatively inexpensive means. Otherwise, companies lacking proper financial support would find it hard to implement circular practices as only large businesses are able to provide themselves with enough finances to do so. Financial risk and uncertainty are an important factor impeding further adoption of practices associated with a circular economy. First of all, such initiatives usually imply use of innovations, new business models, and changes in regulations, which results in uncertainty regarding future profits. Moreover, the economic viability of recycling and manufacturing requires consideration of unpredictable prices for both virgin and secondary materials. If the former is lower than the latter, circular practices become unprofitable [7–10,14–16,45,84,97]. Another significant aspect pertains to the change of the business model. A number of circular approaches lead companies to abandon the classical way of generating revenues through selling products and embrace service models such as PaaS, leasing, or sharing services. Although such an approach results in relatively stable income sources, it is associated with delayed profits and the need to have possession of assets. Hence, this changes the whole mechanism of the cash flow and makes businesses re-evaluate their financial planning and accounting practices. The involvement of the financial system plays a critical role in the circular transition process as it provides an infrastructure that determines which activities will receive funding and how investments are evaluated. Nevertheless, traditional financial systems might be unable to properly assess such ventures due to the bias towards short-term profits.

Incorporation of ESG criteria into financial decision-making is another major development that contributes to aligning financial incentives with circular goals. Growing usage of green bonds, sustainability-related loans, and impact investments is helping to promote circular activities, though their scope is still rather limited compared to global needs for investment. Another vital tool for creating favorable financial conditions is public policies that can affect the financial situation through economic incentives and regulations. Subsidies, tax breaks, carbon prices, and EPR systems can have a great effect on the profitability of the proposed changes in a company's practices. For example, imposition of taxes on virgin material extraction or landfill operations may result in reduced cost advantage of using such materials. Moreover, state support of research and development will help to decrease technological risks and facilitate innovation. However, contradictions between national policy frameworks can cause uncertainty and negatively affect cross-border investments. As for macroeconomic considerations, transition towards circular economy has certain implications for capital and labor allocation [4,35–44]. Circular practices are expected to lead to transformation of the industrial sector towards knowledge-based and service-related activities. However, this shift might also create transition costs, such as stranded investments in conventional industries and skills upgrading for workers. Financial systems will thus have to facilitate not just the investment in new circular business models but also the phased reduction of unsustainable industries.

Last but not least, financial performance measurement and evaluation also present difficulties in the context of the circular economy model. Established methods of measurement might not fully assess the financial value of the circular model, especially considering that the circular model is characterized by greater resilience and sustainability, resulting in better financial performance. New financial measures and methods for assessing circular economic activities are therefore needed. Conclusively, financial problems play an essential role in the process of implementing circular economy, affecting how fast and extensively it can be adopted. Although there are substantial challenges regarding investment costs, risks, and other barriers, some ways to tackle these issues include the use of various financial instruments and business models. The conceptual relationships among the main dimensions of the circular economy are visualized in **Figure 5**.

Figure 5 displays a framework of financial aspects related to the transition towards the circular economy. In the **Figure 5**, there are shown major elements in terms of financial drivers, constraints, and system enablers that have been mentioned in the above sections of this chapter. The central aspect of the framework is the transition to the circular economy that depends on internal aspects of businesses such as their ability to invest, risks, and restructuring. External elements like financial systems, policy environment, and macroeconomic changes influence the transition process. Thus, the transition to a circular economy is not only a technological and ecological issue but also a complex financial shift.

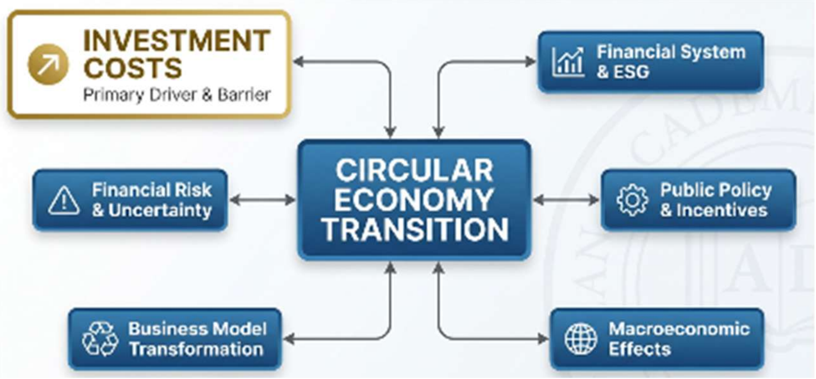

Figure 5. Financial dynamics of the circular economy transition (authors' scheme).

14. Results and discussion

The material throughput in society continues to intensify, exacerbated by the steady decline of product life spans. The unsustainable consumption and rapid depletion of natural resources have extended into production operations. Linear production and consumption practices, enduring since the Industrial Revolution, are now being complemented or even supplanted by circular material flows capable of delivering substantial resource efficiency improvements [137,138]. Considering that the subject matter is widely debated in terms of circular economy, this paper will not seek to discuss all of them in relation to empirical validation of the research hypotheses. As such, the paper adopts the selective synthesis approach that concentrates on the most relevant sectors in which there exist identifiable operations of the mechanisms of applying the concept of circular economy. Moreover, the discussion of different sectors like manufacturing, construction, agriculture, and textiles is not for empirical findings by sector but rather to illustrate the universality of the conceptual framework across sectors. Design strategies must incorporate material resource efficiency across entire product life cycles, employing resource-saving tactics such as reuse, repair, remanufacturing, and recycling to grant products a "new lease on life". The circular economy constitutes a concerted effort to integrate economic activity with environmental and resource objectives on a sustainable footing—combining resource efficiency with economic performance—and subsequently, the production of conventional goods with enhanced social and economic benefits. Since the turn of the twenty-first century, policies oriented to boosting resource efficiency have evolved at a rapid pace on a global scale, driven by the impact of a globalized market and increased awareness of resource scarcity. A handful of global players—including Japan, the European Union, and China—have already mounted dedicated policy efforts [6,7,9–12,14,15,38,40,45,82–84,121,124]. The European Commission's comprehensive action plan for a transition to a circular economy specifies the principal policy interventions required across a product's entire life cycle. A holistic policy mix, oriented at the system level, is needed to make sense of the sheer complexity and to single out the most relevant aspects of this transition.

Emerging innovations play a crucial role in the development of resilient circular economies and the facilitation of a circular (closed-loop) economy for both materials and industries. They enable a shift in the flow of materials from being continuously linear to closed, interconnected, and cyclical throughout the economy. By significantly improving and accelerating resource efficiency, these innovations contribute to the redesign and creation of circular business models and production systems. Key commercial materials such as steel, plastics, aluminum, glass, and timber are sold, processed, re-melted, re-forged, and reshaped in one country, only to be imported as waste for recycling elsewhere. Several frameworks emphasize the need for global co-operation and open innovation. Well-developed institutions must be complemented with appropriate capacity, incentives, equal access, and global competitiveness. Co-ordination of different actors with varied interests can be achieved through inclusive policies, transparent knowledge exchange, open competition, and the practical implementation of circularization programs [47–59]. The ambition is to encourage an entrepreneurial ecosystem conducive to accelerating innovation through commercial, environmental, and social interconnectedness. Global co-operation programs serve to aggregate knowledge and share experiences. For the public sector, knowledge sharing requires open innovation platforms and a workforce that is capable of innovation and technology absorption. International blueprints, such as the United Nations' 2030 Agenda for Sustainable Development with its 17 Sustainable Development Goals, account for global economic, societal, and environmental issues. The roadmap from the Organization for Economic Co-operation and Development (OECD) comprises five focus areas, which deal with capital, profit, and value distribution in the Global South, the costs and benefits of trade, the material footprints of the rich, and the coordination of global governance. Global co-operation programs further need to tackle the inherent complexity and uncertainty of an entrepreneurial ecosystem via specific regulation. Regulations must also respond to trade-offs in supply and demand, such as the recent trade concerns expressed by the G7 nations [139,140]. The European Union's consumption of rare earth elements is disproportional to that of production, with the result that supply is highly vulnerable to disruption. Understanding the fate of key metals in urban mine analogues is critical if the circular economy is to become a reality. International co-operation programs will be pivotal to the future transition [4,28–45,61–69]. Open innovation complements global co-operation by facilitating the interactive development of innovations, improvement of existing knowledge bases, and the imitative adoption and adaptation of both. The main characteristics and synthesized conclusions derived from the analysis are presented in **Table 2**.

Table 2 shows that Characteristics, Historical Conclusions, Historical roots, CE evolved from concepts such as industrial ecology, cradle-to-cradle, and performance economy, emphasizing system resilience and material circulation. Environmental impact CE reduces waste, emissions, and resource depletion by designing closed loops that extend product lifespans and minimize pollution. Economic benefits: Transitioning to CE lowers material costs, stabilizes supply chains, creates new business models (e.g., product-as-a-service), and generates employment. Social benefits CE promotes job creation, poverty reduction through second-hand markets, lifestyle improvements, and enhanced well-being. Technological barriers, resistance to reengineering, quality concerns in recycled materials, and limited adoption of new manufacturing methods slow down the CE transition. Regulatory issues: Extended Producer Responsibility (EPR) is crucial but requires stronger enforcement, broader scope, and better monitoring mechanisms [141,142]. Digital innovation tools such as IoT, blockchain, digital twins, and AI improve tracking, transparency, and optimization of resource flows. Sectoral applications CE is especially relevant in manufacturing, construction, agriculture, and textiles, where material flows and waste are significant. Consumer behavior, awareness, education, and cultural change are essential to encourage repair, reuse, and recycling at the household and community level. Future trends: International cooperation, open innovation, and global policy frameworks will determine the speed and scale of CE adoption. Open-innovation principles encourage the sharing of ideas across business lines and industry boundaries in order to achieve collective competitive advantage. Co-ordination of resources may take place through gatherings or networks, which can be physical or virtual, single- or multi-industry, local or global, informal or formal, supply- or demand-focused. Although the circular economy paradigm is repeatedly described in literature as a sustainable alternative, the current study recognizes that its application faces substantial debate, compromise, and restrictions. Some researches identify the presence of a rebound effect, where efficiency improvements can increase total consumption levels and negate environmental advantages. Additionally, practical applications may face certain structural challenges, such as expensive transition expenses, technological limitations, lack of regulation, and cultural opposition. Moreover, the advantages of circular processes cannot equally impact all industries or countries and might even create unintended consequences in terms of socio-economic inequity in certain scenarios. That is why the results of this study can be viewed as an impartial summary of opportunities and restrictions, not a normative recommendation for implementing the circular economy model.

Table 2. Conclusions about economy and closed-loop systems (Authors' table).

Characteristics	**Historical conclusions**
Historical roots	CE evolved from concepts such as industrial ecology, cradle-to-cradle, and performance economy, emphasizing system resilience and material circulation.
Environmental impact	CE reduces waste, emissions, and resource depletion by designing closed loops that extend product lifespans and minimize pollution.
Economic benefits	Transitioning to CE lowers material costs, stabilizes supply chains, creates new business models (e.g., product-as-a-service), and generates employment.
Social benefits	CE promotes job creation and poverty reduction through second-hand markets, lifestyle improvements, and enhanced well-being.
Technological barriers	Resistance to reengineering, quality concerns in recycled materials, and limited adoption of new manufacturing methods slow down the CE transition.
Regulatory issues	Extended Producer Responsibility (EPR) is crucial but requires stronger enforcement, broader scope, and better monitoring mechanisms.
Digital innovation	Tools such as IoT, blockchain, digital twins, and AI improve tracking, transparency, and optimization of resource flows.
Sectoral applications	CE is especially relevant in manufacturing, construction, agriculture, and textiles, where material flows and waste are significant.
Consumer behavior	Awareness, education, and cultural change are essential to encourage repair, reuse, and recycling at the household and community level.
Future trends	International cooperation, open innovation, and global policy frameworks will determine the speed and scale of CE adoption.

15. Discussion

In order to improve the interpretative power of the discussion, a conceptual heatmap is used to visualize the main thematic dimensions discovered through the analysis. As it should be recalled that the current study applies to theoretical and conceptual research rather than empirical, the heatmap cannot be considered as statistical evidence but demonstrates the interaction among and levels of significance of key discussion topics. Elements such as environmental sustainability, economic efficiency, social effects, governance structures, and innovation dynamics all contribute to the creation of a shift from linear to circular economies. All of these elements can be visualized in a single map as per qualitative consideration of the existing literature on circular economics. Through the help of this heatmap, it is possible to see how the different factors influence the formation of the complex system.

The map is designed to show the degree of interaction between various dimensions that form part of the circular economy concept. However, this is just a visual illustration of a certain pattern rather than a proof of the fact that one or another dimension carries greater significance than others. The conceptual heatmap is presented in **Figure 6**. **Figure 6** displays the conceptual heatmap that has been produced by means of qualitative synthesis from the existing body of knowledge. As for the selection of the dimensions represented in the heatmap, such selection was made on the basis of the most frequent occurrences of certain topics in the literature under review. It should be noted that the intensities of the links connecting different dimensions have been assessed in accordance with how strongly the interconnection of certain topics was emphasized in previous studies. These intensities are not measurable through any calculations; rather, they are simply compared through thematic analysis.

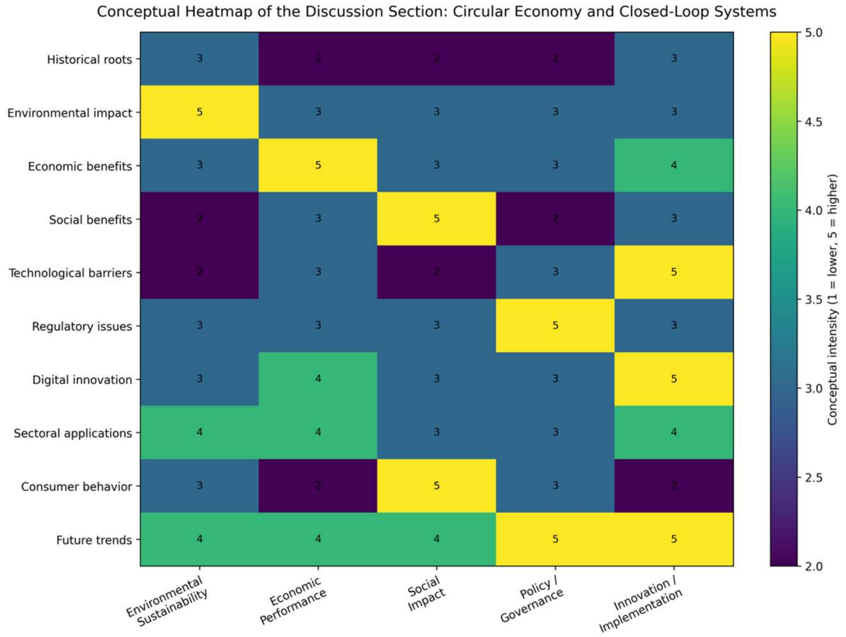

Figure 6. Characteristics of the circular economy (authors' scheme).

Figure 6 shows that the adoption of the circular economy system has a multidimensional nature, where some topics indicate a more intense relationship with each other. For paradigm, environmental impact and future trends are highly important for the successful implementation of the concept, which is associated with the significance of sustainability and systematic changes in terms of transitioning towards circular systems. Digital innovation and regulations also represent strongly interconnected aspects, showing that the development of technology and creation of an enabling governance system are among the most important aspects when adopting circular models. Economic benefits are also found to be strongly correlated with innovation and sector applications, meaning that there are economic drivers behind circular practices. At the same time, such aspects as consumer behavior and social impact play a crucial role but are less intense compared to others. Whereas the present study focuses on the role played by financial aspects in the transition towards a circular economy, this is not to imply that other limitations do not matter. Technological lockins, regulatory fragmentation, cultural resistance, and industry-related traits can all be considered major obstacles, possibly interlinking and working together in complicated ways. Nonetheless, the role played by financial aspects stands out in this context since they condition the viability of dealing with other obstacles. For example, technology-related issues require substantial funding, regulation can incur certain expenses, and consumer behavior may be shaped by pricing policies and other economic instruments. In other words, financial systems can be treated as either facilitating or complicating the influence of other aspects. At the same time, such conclusions are made based on theoretical synthesis without any attempt at ranking the significance of these variables empirically. Based on the results from the above-discussed analysis, it is clear that there are certain financial aspects that must be considered when implementing the concept of a circular economy successfully. In terms of policies, governments need to encourage circular investments through different incentives like subsidies and tax cuts, along with various forms of green finance like sustainability-related loans and green bonds. The use of pricing strategies like taxes for carbon emissions and landfilling will contribute to correcting market distortions and make it more profitable to operate based on circular systems. When speaking about businesses, it is vital to utilize financial valuation approaches that consider life-cycle costs and sustainability measures. Collaboration among companies within industrial networks will allow for minimizing risks associated with investments and better access to resources. Although this paper uses the conceptual and integrative approach, it is intentional since it aims at providing a thorough review and synthesis of existing literature on the topic of circular economy as well as developing a structured theoretical model. Absence of empirical examination of findings in the study should not be viewed as a limitation of the study since it aims at advancing the theory on the issue and exploring possible interrelationships in the context of circular economy. On the other hand, interpretive nature of the study allows combining different viewpoints from various sources in order to get a holistic picture of circular economy dynamics. While the broad scope of the study focuses on generalizability of findings, future researches can use these results in order to conduct further empirical studies on the subject matter.

16. Conclusion

Even though financial considerations arise as one of the most important factors when moving toward circular economy models, their significance needs to be acknowledged as just one part of a multidimensional set of constraints. This is true since financial factors have an especially significant impact on investment capabilities, risk-taking, and economic feasibility. Nonetheless, their effects cannot be isolated from issues related to technological maturity, institutional conditions, and sociocultural trends. Thus, it would be appropriate to interpret the results of the research as showing that financial factors play a key role within the constraint system rather than dominate it. Emerging economic development frameworks offer pathways to preserving resources, decoupling growth from environmental degradation, and enhancing prosperity and well-being. The circular economy stands as the most prominent among such frameworks, central to European Commission policy, and widely embraced by industry. Historical roots of circular thinking trace back to industrial ecology and performance economy concepts, with the foundational principle that economies should operate within the planet's biophysical thresholds underpinning cradle-to-cradle, performance economy, and biomimicry approaches—all converging within the circular economy umbrella. It rests on resource circulation and system resilience principles, as illustrated in merged supply and waste chains and natural material flows. The circular economy framework combines resource recovery, enhancement of resource value through design, and waste reduction by design. The interaction of these components enables a comprehensive transition from linear to circular systems. The circular economy is conceptualized as a resiliency framework tailored to the contemporary, industrial world, positioning it as a linchpin of sustainable development.

Circular Economy becomes a universal approach that enables balancing economic growth and environmental sustainability through efficient use of resources, waste reduction, and resilience building. This process is evident from the entire research on the development of the theory from industrial ecology and closed-loop systems to current circularity. Nevertheless, despite the environmental and social benefits of the circular economy, the move to circularity is essentially influenced by monetary factors.

A key observation emerging from this analysis is that financial considerations represent a critical enabling factor influencing the speed and scale of circular economy adoption. While they play a central role in shaping investment decisions and implementation feasibility, their importance should be interpreted in conjunction with technological, regulatory, and social dimensions, which jointly determine the overall transition dynamics. The high costs involved in making significant investments to redesign their products, establish a reverse logistics chain, and create necessary infrastructure serve as a significant obstacle, especially for small and medium-sized companies. Further complicating matters is the risk and uncertainty surrounding finances arising from material prices and regulatory dynamics. The shift to circularity involves a complete restructuring of the way businesses earn revenues, as many organizations move towards service business models where cash flows are changed, thus affecting the time required to recover investments. From a systems perspective, the importance of financial considerations cannot be understated since financial institutions and green finance play critical roles. Financial evaluation methods typically emphasize short-term profitability rather than sustainability, leading to an undervaluation of the benefits of circularity. To address such challenges, ESG considerations, green finance instruments, and public policies must be utilized. Although the circular economy presents promising opportunities for sustainable development, its adoption is hindered by certain economic barriers that require changes in the current financial system for its proper functioning. This means that it will be important to adopt a coherent strategy to promote the transition to the circular economy by means of financial instruments.

Author contributions: Conceptualization, CC; Methodology, CC; Software, CC; Validation, CC and DV; Formal analysis, CC and DV; Investigation, CC; Resources, CC, NE, and DV; Data curation, CC and DV; Writing—original draft, CC; Writing—review & editing, CC; Visualization, CC, NE and DV; Supervision, CC, NE and DV;

Project administration, CC, NE and DV; Funding acquisition, NE and DV All authors have read and agreed to the published version of the manuscript.

Funding: None.

Conflict of interest: The authors declare no conflict of interest.

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