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REVIEW

Circular Economy and Ecosystem Services: Advancing Sustainable Resource Management for the Future

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ABSTRACT

The concepts of the circular economy (CE) are actively popularized as ways of minimizing waste products and the need to rely on virgin resources. Nevertheless, their sustainability is doubtful at a general level where ecosystem functioning and ecosystem services (ES) are not given explicit attention. This review will combine both conceptual and empirical evidence of the connection between CE interventions and ES outcomes to enable more sustainable management of resources. We describe the effects of the CE strategies on the key environmental pressure pathways, altering ecosystem conditions, and impacting the delivery of regulating, provisioning, and cultural ecosystem services using a pressure condition-service framework. Analysis reveals that demand-side reduction and product life-extension strategies tend to offer more consistent ecosystem service co-benefits than recycling and recovery strategies because they do not involve production, and will cause less disturbance to the upstream environment. Contrastingly, recycling and recovery sustainability performance is highly dependent on the sources of energy, intensity of processing, and the safety of materials. Bio-based circularity has the potential to increase soil functionality and nutrient cycling, and mass application will result in trade-offs in terms of land competition and nutrient leakage. The sectoral analysis identifies the unique opportunities and threats in the agri-food systems, the built environment, plastics and textiles, electronics and critical minerals, and water and wastewater systems in terms of the burden displacement, local environmental pressures, and equity concerns. Harmonized reporting, coupled with supply-chain and spatial ecological assessment, threshold-conscious strategies that promote safe and regenerative circular systems should be put into the line of future research.

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1. Introduction

The ever-increasing demand rates of natural resources and the rising environmental strains of climate change, biodiversity loss, and waste generation have highlighted the dire necessity of more sustainable systems of resource management[1,2]. The industrial model of take, make, and dispose that has been practiced for centuries in industrial practice has resulted in the exhaustion of natural capital, environmental degradation, and more waste produced. Conversely, another important concept has been floating, and that is the Circular Economy (CE) as a possible paradigm shift in the way we think about production, consumption, and waste. CE aims at limiting waste generation, improving the product lifecycle, and limiting the use of virgin resources by targeting the material loops closure, thereby providing a way to more sustainable and resource-efficient systems[3].

Although CE has some obvious benefits regarding waste minimization, emission, and resource mining, it tends to ignore one of the most important parts of the sustainability concept, the significance of ecosystems promoting human well-being[4]. Life on Earth is based on ecosystem services (ES), which are described as the benefits that ecosystems offer to people, like clean water, air, fertile soil, pollination, and even climate regulation. Although ecosystems are central to the maintenance of all life on earth, their importance is either underestimated or not sufficiently integrated into economic modeling, as well as sustainability policies and frameworks. Consequently, despite the number of beneficial effects of reduced material flows and waste, many circular economies approach unintentionally impose further loads on the ecosystems, with some negative effects being unintended and negatively affecting biodiversity, the health of the ecosystem, and long-term sustainability[5–7].

The purpose of this review is to close the gap between the Circular Economy and Ecosystem Services by ascertaining the overlaps between the two terms and driving the adoption of ecosystem services in the process of sustainable management of resources. Although the Circular Economy is proclaimed as the solution to resource inefficiency and waste, it must be considered not only in the context of material and energy-saving but also in the context of the influence on ecosystem integrity[2]. The key issue is how the strategies of CE can be constructed and carried out in such a manner that both will minimize the human presence on natural resources and will be able to sustain or even reestablish the operations of ecosystems delivering vital services[8].

Such integration is needed urgently. With the transition of society toward more circular systems, there is a need to guarantee that these systems do not merely push the pressure of the environment to a different area, but they should actively work towards the regeneration of ecosystems[9]. Unintended ecosystem impacts of circular strategies, including recycling, bio-based material recovery, and industrial symbiosis, in most instances, include intensifying land-use change, the danger of habitat loss, and biodiversity loss. As an example, the use of bio-based substances in the bioeconomy may contribute to the further development of agriculture, which has adverse effects on carbon sequestration, water quality, and soil fertility[10]. On the same note, recycling may cause the release of toxic chemicals or the buildup of non-biodegradable wastes in the ecosystems, defeating the same objectives in such a process that sustainability aims to attain[11].

In order to overcome these limitations, this review summarizes the new body of research findings on the connection between Circular Economy strategies and ecosystem services. In particular, it discusses various issues, such as the effect of various CE strategies, including design to survive longer and product life extension, recycling, and industrial symbiosis in terms of the different types of ecosystem services, including provisioning, regulating, cultural, and supporting services[12]. Through the analysis of these interactions, the review will seek to present a more holistic approach to developing circular systems that will be beneficial in terms of ecological health and resilience, as well as protecting the ecological services that the ecosystems offer to society.

More so, the paper will discuss the techniques and instruments that may be employed to measure the cumulative effect of the CE and ES, material flow analysis (MFA), life cycle assessment (LCA), ecosystem service modeling, and natural capital accounting[13]. Through their combination, a more holistic approach to assessing the sustainability of circular systems can be developed, which not only considers the efficiency of the resources but also looks at the well-being of the ecosystems in the long term.

It is not only that ecosystem services need to be integrated into Circular Economy frameworks to establish environmental sustainability, but it is also necessary to guarantee social and economic resilience. Human well-being has its basis in ecosystem services, which also aid human beings in food security, clean water, clean air, and a stable climate[14,15]. The strategies of the Circular Economy can also help the broader sustainability outcomes, including the realization of the United Nations Sustainable Development Goals (SDGs), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13)[16].

The review further seeks to provide viable suggestions to policymakers, businesses, and researchers to transcend silo thinking in regard to sustainability. It supports an approach that is more integrated, connecting circularity, ecological health, which should create a regenerative circular economy, and respect and restore the ecosystems on which all life relies[8]. It allows fostering a paradigm shift, not only aiming to ensure material looping but also restoring the liveliness of the ecosystem, making everyone have a sustainable and fair future.

This review aims to aid a more holistic approach to sustainable resource management, which is more balanced and holistic, and which takes into account the fact that human systems and natural systems are interconnected, making the future more sustainable.

2. Conceptual Foundations and Analytical Framing

This part forms the conceptual foundation of the integration of circular economy strategies and ecosystem services to aid in the sustainable management of resources. It elucidates the main constructs, points at the places where their assumptions coincide or contradict each other, and provides an analytical framing that connects circular interventions to ecology using quantifiable channels. This is needed as circularity is often measured in terms of material-centric indicators, whereas the ecosystem is judged based on ecological structure, function, and resilience, which are defined by spatial heterogeneity, time lags, and non-linear relationships[17]. This review uses a conceptual framework of pressure-condition-service (**Figure 1**) in order to explain the systemic interaction between circular economy strategies and ecosystem service outcomes; how CE interventions alter environmental pressures, which cause changes in ecosystem condition and ecosystem service provision.

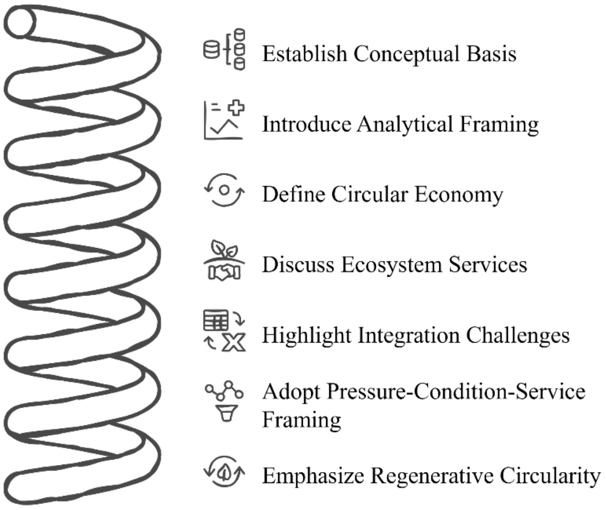

Figure 1. Schematic representation of the relationship between the interventions of the circular economy and ecosystem services in a pressure condition service pathway.

The circular economy strategies alter the environmental pressures, including resource extraction, emissions, and land use, which influence the ecosystem condition, ultimately defining the provisioning, regulating, and cultural ecosystem services delivery.

2.1. Circular Economy as a Resource Management Paradigm

The concept of the circular economy is generally introduced as an alternative economic organization mode to the linear one, which strives to minimize the primary resource extraction and waste production by ensuring products, components, and materials can be repurposed as long as possible[18]. As its name suggests, CE includes a family of strategies that are implemented at various stages of the life cycle, such as demand reduction and designing the product, life extension, re-use, remanufacturing, recycling, and recovery. These are sometimes termed as loops of tightness with the overall assumption that the tighter the loop, the more value the loop would save, such as reuse and repair, compared to looser loops, such as recycling, where the quality of materials can be compromised, and more energy and processing can be involved.

One key theoretical aspect of CE is its focus on efficiency at the system level: cutting through product and service redesign, supply chain reorganization, and more resource productivity[19]. However, CE is not a homogeneous theory, having a consistent boundary. Other interpretations are more concerned with materials and waste, whereas some explicitly regard renewable energy, material cycles that are not necessarily toxic, as well as regenerative, and try to restore ecological systems instead of reducing harm. This array of definitions is important to the sustainability assessment, since CE interventions may have entirely different environmental characteristics, depending on the technologies embraced, a type of energy system that supports circular operations, the material composition and toxicity of products, and the institutional contexts that influence implementation[8].

Boundary setting is hence an issue of definition in CE analysis. System-level consumption adjustments can go together with product-level consumption, a problem that is commonly referred to as rebound. Likewise, the cyclical advantages in a given area might be redirected to other areas by means of trade and the international chain of supply. These leakage effects make it difficult to assert claims that an increase in circularity necessarily means a reduction in environmental pressure. Besides that, circular strategies can create different types of impact, such as expanding transport and logistics to reverse supply chains, heightening sorting and reprocessing demands, and exposing the likelihood of accumulating dangerous materials through recycling. As a result, CE should not be defined as the mere practice of closing loops, but as a set of interventions that reconfigure pressures on both natural and human systems to some degree of beneficial, neutral, or harmful ways, depending on the situation[20].

2.2. Ecosystem Services, Natural Capital, and Ecological Integrity

Ecosystem services (ES) refer to benefits that ecosystems contribute to human well-being that include material benefits like food and timber, regulating benefits such as water purification and climate regulation, and cultural benefits like recreation and a sense of place[15,21]. ES concepts are directly related to natural capital, which positions ecosystems as a stock of natural resources such as soil, forests, wetlands, biodiversity, and ecological processes that create flows of services over time. Such a stock-flow differentiation is essential to sustainability since it is possible to attain short-term gain in services at the expense of the underlying natural capital by either exhausting or damaging it, leading to losses in the long term and a lack of resilience.

One of the main implications of ES framing is that, through aggregate measures of resource use alone, environmental change is not well represented[22]. The ecosystems are spatially particular, multi-purpose as well, and controlled through the communication among species, environment, and biophysical procedures. Due to them, service provision can be impacted by changes in land use, water withdrawals, pollutants, and climate in ways that are location-dependent and even irreversible[19]. ES responses are characterized by many time lags, threshold behavior, and non-linearities. Indicatively, the water quality may be destroyed due to nutrient loading beyond a tipping point, and afterwards, the restoration process may prove slow and unpredictable despite a decline in pressures. These properties suggest that sustainability must be concerned with not only ecological state and stability, but also material throughput cuts.

Trade-offs are also to be taken care of in ES assessments[23]. Providing more through an increase in biomass production may serve regulatory services like carbon storage and flood control, through the loss of habitat integrity or a change in hydrological regime. Similarly, one intervention that enhances a service in a specific location can cause a decline in the other service in another location, especially when displaced land use and the supply chains are factored in. Since ES are anchored in social values and institutional contexts, distributional questions are also posed. The positive externality of ecosystem services, as well as the negative externality of ecosystem degradation, is not distributed globally across communities, income groups, and generations in a balanced way. The linkage of CE to ES must thus muster up any form of structure that embodies not just bio-physical excitations but the governance and equity terms of service flows, generation, and experience. **Table 1** summarizes the links between circular economy plans and types of ecosystem services. The table depicts that various CE strategies, such as demand reduction, product life extension, recycling, bio-based circularity, and systemic reconfiguration, can affect provisioning, regulating, and cultural ecosystem services. Although most of the strategies eliminate the environmental pressures by lowering the extraction of resources and minimizing the generation of wastes, others can have mixed ecological effects depending on the design of the system and the magnitude of the implementation[24].

Table 1. Crosswalk between circular economy strategy families and ecosystem service categories.

CE Strategy Family	Typical Interventions	Primary Pressure Pathway Changed	Ecosystem Services Most Directly Affected	Likely Direction (General)	Common Risks/Conditions
Demand-side & design (refuse/rethink/reduce)	dematerialization, product-as-a-service, shared use, eco-design	↓ extraction; ↓ production emissions; ↓ waste	regulating (climate, air/water regulation), supporting (habitat integrity)	Positive (often strongest)	rebound; burden shifting via trade; composite materials increasing end-of-life complexity
Life extension (reuse/repair/refurbish/remanufacture)	repair networks, refurbishment, remanufacturing	↓ extraction; ↓ manufacturing burdens	regulating (climate), supporting (habitat), some cultural (reduced nuisance)	Often positive	inefficient legacy tech; hazardous legacy materials; informal processing impacts
Recycling & recovery (recycle/recover)	mechanical/chemical recycling, material recovery	↓ virgin extraction but ↑ processing burdens	regulating (water/air quality), supporting (biodiversity via avoided mining)	Mixed/conditional	toxic circularity; downcycling; localized burden concentration; energy/water intensity
Bio-based circularity & nutrient loops	composting, anaerobic digestion, biochar, nutrient recovery	↓ landfill methane; ↑/↓ nutrient loading; land pressure	supporting (soil function), regulating (climate, water regulation)	Mixed/conditional	land competition; nutrient leakage/eutrophication; feedstock sourcing constraints
System-scale reconfiguration	industrial symbiosis, circular cities, urban mining	↓ waste; ↓ extraction; spatial redistribution	regulating + cultural (urban heat/flood mitigation; amenity)	Context-dependent	infrastructure lock-in; siting equity; coordination failures

2.3. Why Is Integrating the Circular Economy and Ecosystem Services Conceptually Challenging

Even though CE and ES are both motivated by the broad concept of sustainability, they are rooted in the diverse traditions of analysis and tend to have different units of analysis. CE usually focuses on the material and economic value retention, as measured by the recycling rates, the material circularity, the product lifetime, or the relative material share[25]. ES frameworks give precedence to the ecological functions and human well-being deliverables with metrics of the condition of the habitat, hydrological functioning, stored carbon, biodiversity integrity, or access to services[26]. Such disparities may create conceptual and practical inconsistencies in the situation where CE performance is used as a measure of ecological sustainability.

The mismatch between interventions and ecological outcomes in terms of scale is one of them. Most CE decisions are made either at the product, facility, or firm level, whereas ecosystem services are usually considered at the landscape, watershed, or region level[24]. This diffuse, global good is willing to be conferred by a circular strategy that avoids the extraction pressures due to virgin materials but has its local impacts on local ecosystems through the production of concentrated emissions, waste residues, or water impacts in particular communities. On the other hand, nature-based circular approaches like organic waste composting or the use of biochar can produce very localized benefits in soil services, whilst also posing systemic risks in both cases, should the increased demand for biomass use lead to the conversion of land elsewhere[27].

The other difficulty is that CE has the potential to change the composition and routes of pollutants rather than their levels. Recycling materials may result in the cycling of hazardous materials unless the design of products and regulatory measures can avoid the possibility of toxic loops. In this instance, circularity may also be used against the objectives of ES, degrading water quality, soil health, or biodiversity with long-lasting contaminants. Such an issue is more relevant to complex products with mixed materials and additives, where safe recycling is technically feasible, but does not necessarily mean equilibrium between eco-compatibility[28].

The third problem is indirect effects and displacement. Circular interventions are often evaluated with a focus on circular systems that miscalculate the trade-associated changes in land use and energy demand, as well as extraction. As an example, a replacement of fossil-based inputs with bio-based ones can decrease the reliance on nonrenewable sources but raises the land and water pressures, which has an effect on carbon storage, intact habitats, and water management. Equally, resource efficiency can be better, resulting in decreasing unit impacts but triggering demands, and eliminating net benefits. The dynamics imply that when combining CE and ES, indirect effects should be explicitly modeled, and both the regulative role of incentives, markets, and consumer behavior should be sensitive to the way total environmental pressures on ecosystems can be reconfigured[24,29].

2.4. An Analytical Framing Linking CE Strategies to Ecosystem Service Outcomes

In order to make CE linked with ES in a decision-relevant manner, this review assumes a pressure condition service framing with circular strategies being discussed as interventions that change environmental pressures, which subsequently influence ecosystem condition and eventually flow of services to people[30]. Circular actions in this perspective modify a combination of pressure pathways, such as intensity of extraction, land use change, water bottlenecks, energy demand, and related carbon dioxide, and release of pollutants. Such pressures alter the ecological structures and processes, including soil organic matter, species composition, hydrological regulation, and trophic interactions, which form the basis of the provision of ecosystem services. Depending on the context of the decision, the resulting ES results can be in terms of biophysical, welfare, or multi-criteria terms.

This articulation explains the contingency of outcomes and not the determinism of results. Various ES effects can arise when the same CE strategy is applied, depending on the location and application method, technologies deployed, the cleanliness of the energy system, the restrictions on hazardous materials prescribed by the economic laws, and the political structures that impact land and water management. It also stresses that the concept of net sustainability cannot be deduced based on circularity only and that it needs to be considered in the perspective of decreased pressures, stabilized or better ecosystem status, and steady or even enhanced service streams[9,24].

Notably, the model caters to both trade-offs and synergies. The tendency to demand fewer and extend the lifespan of its products is likely to ease the upstream extraction pressure, contributing to habitat conservation and service regulation, but will realize gains according to the adoption rate and rebound[31]. Recycling may decrease mining stress but might augment local discharges and wastes, which will impact the local ecosystem and community. The bio-based circularity can enhance the cycling of nutrients and soil functions on local scales, but impose the pressure of land-use on scale. Circular configurations on the system-level, e.g., industrial symbiosis or circular cities, should generate an important set of co-benefits in the event of coordination with a spatial planning approach and ecosystem conservation, but become lock-ins of infrastructures prone to concentrate burdens when they are not governed considering siting, equity, and ecological limits[32].

2.5. Toward Regenerative Circularity within Ecological Thresholds

One last conceptual component is that of a difference between logical circularity and the idea of the real results. There is a need to reduce throughput and waste of materials, but this might not be enough in a world where the ecosystems are already compromised and where there is a growing risk to climate and biodiversity. CE has a regenerative version that makes ecological thresholds and restoration goals the center stage of the circular design. According to this perspective, circular strategies are not judged on their effectiveness in closing loops but on whether they can be useful in ensuring ecosystem integrity, resilience, and recovering essential services, including climate regulation, water purification, flood mitigation, and soil fertility[12,20].

This recognizable threshold view re-examines sustainable management of the resource as a social ecological dilemma. It means that the targets of CE must be determined as per the ecosystem capacity and vulnerability, that the cycles of hazardous materials must be highly controlled with no further ecological damages, and that decentral shifts have to be evaluated regarding distributional effects[33]. This conceptual basis is applied throughout the rest of the article, both to explain the evidence on the interaction of various circular strategies with the ecosystem services within the sector and scales, and what conditions underlie the plausibility of the idea of circularity to promote long-term sustainability.

3. Mechanisms Linking Circular Economy Strategies to Ecosystem Service Outcomes

The causal pathways that exist between ecological change and socio-technical interventions mediate the relationship between circular economy strategies and ecosystem service outcomes[34]. Circular interventions change the size, structure, timing, and place of material and energy circulation, and this redefines the pressures acting upon the ecosystems. These stresses affect the condition of the ecosystem by altering the habitat structure, biogeochemical cycles, hydrological regimes, and exposure to contaminants. The ecosystem condition, in turn, defines the level of the quantity and quality of the ecosystem service flows that help to maintain human well-being. It is important to learn about these processes in order to avoid the widespread premise that when we enhance the measures of circularity, we inevitably get environmental gain. Practically, an identical circular strategy can produce gains, trade-offs, or net losses in ecosystem services in relation to system boundaries, technological decisions, governance configurations, as well as the ecological setting in which it takes place.

3.1. Pressure Pathways as the Bridge between Circular Interventions and Ecosystem Services

Circular strategies act by altering the pressure ways attached to the linear economy, such as primary extraction, land conversion, atmospheric and water emissions, waste discharge, and piling up of persistent pollutants[35]. The circular interventions in the form of demand for virgin materials can reduce the pressure of extraction upstream, which is closely associated with habitat destruction, soil disturbance, water deprivation, and loss of biodiversity[36]. By minimizing waste production and uncontrolled waste, they can lower pollution burden and physical littering in both land and water resources, as well as contribute to the control of such regulating services as water purification and climate control. Yet, circularity may also cause certain pressures, such as escalation during the course of sorting, transport, and processing, the growth of bio-based production, which will compete with land and water, or consistent recycling of hazardous substances.

The mechanism-based perspective thus attests that circular interventions ought to be determined using alteration in pressure intensity and pressure composition, as opposed to loop closure. The composition of pressures is especially significant to ecosystem services since ecological reactions are delicate to the type, timing, and cumulative exposure of contaminants[37]. To consider, small variations in the nutrient loading could have minor effects in certain systems, but will cause eutrophication in others with a low assimilative capacity. Similarly, the decrease in the levels of bulk waste could not mitigate the ecological damage in case toxic components are not handled or transferred throughout the regions.

3.2. Extraction Displacement and Avoided Land-Use Change

Avoiding primary extraction is one of the most commonly claimed ecological advantages of the strategies of a circular economy[38]. A longer product lifetime, reusing products, and replacing virgin inputs with previously used materials can help the circular system lower the mining, logging, and extraction activities, converting the land to other uses, which causes conversion and disturbance of habitats. The likely result of avoided extraction on the ecosystem service is potentially large since, in most instances, extraction has numerous effects, such as provisioning services through effects on local resource availability, regulating services through sedimentation and water contamination, and cultural services through landscape change and recreational value loss[39].

Displacement and market structure, however, mediate this mechanism. The stopped extraction in one area can be balanced by an increase in extraction in other areas because the demand keeps up, or because the secondary materials are inefficient due to the quality or price variations, or supply insecurity. Besides, the effects of extraction are spatially discontinuous; by downscaling mining in a biodiversity hotspot, the benefits to ecosystem services can be significantly greater than downscaling extraction in already-degraded regions. Such considerations suggest that the ecosystem service benefits are not solely as a result of aggregate societal losses in virgin material usage, but in where extraction is shunned, where ecosystems are not breached, and where no substitution is maintained (under realistic market circumstances) [40].

3.3. Pollution Reduction and Ecosystem Recovery Dynamics

The emission and waste leakage of ecosystems have the potential to enhance ecological recovery by means of circular strategies that improve ecosystem services [24]. The collection of waste can be improved, the design of the products so that there would be a minimum amount of hazardous substances, and the recovery of the materials would help to decrease the amount of pollutant load into the waters, soil, and coastal ecosystem. Such minimizations are able to superempower the regulation of services such as water purification, disease control, and climate control by means of healthier wetlands, soils, and vegetation. Circular organic waste management strategies and green-belt structures in cities can mitigate stormwater contamination to enhance the state of aquatic ecosystems and their recreational outcomes [41].

This mechanism is not made easy by recovery dynamics. Ecosystems can be slow to react to pressure-based changes as a result of legacy pollution, modified hydrology, or back-trespassing pollutants. Certain systems may display hysteresis, whereby to reverse to the previous level of service, more powerful interventions are needed as compared to those originally that led to the degradation. It implies that as-you-go service response does not indicate that circular interventions should not be judged; monitoring horizons must consider ecological time lags, accumulative stress sources, and the prospect that restoration might take complementary resources beyond resource loop adjustment, like habitat restoration, hydrological reconnection, or cleanup [42].

3.4. Intensification of Processing and Localized Burden Concentration

Although the circularity can decrease the upstream extraction, it can raise the intensity of the downstream processing. Recycling, remanufacturing, and material recovery may demand considerable energy and water supply, produce some residual products of the process, and localize the emission in one or several sites. This forms a process of concentration of load at the local level, where local communities and ecosystems around the processing plants are contaminated with high levels of air pollutants, wastewater release, noise production, and land-use and industrial displacement pressures in relation to industrial location and logistics. The ecosystem service implication may encompass a decrease in the local quality control of air, water purification, and cultural service associated with landscape amenity, especially when the plants are located in tourist areas near potentially vulnerable ecosystems or poorer populations [43,44].

This mechanism shows that spatial distribution and environmental justice are crucial in CE (circular economy) and ES (ecosystem services) integration. A circular transition, which is helpful in a more aggregate sense, may degrade the ecosystem services at certain locations because the processing effects are not carefully dealt with or because the governance framework loses control. Process technology, emission control, source of energy, and siting determine the magnitude of this risk. Clean energy and the best available pollution control applied can lessen the ecosystem service load of processing, but do not remove it, particularly in cases where materials are those of hazardous additives or complicated composite structures [45].

3.5. Toxic Circularity and the Persistence of Hazardous Substances

Another unique risk mechanism with circular systems is toxic circularity, where dangerous materials in products keep being reused with repeated material cycles. Contrary to linear disposal, in which the adequate management of confinement may isolate hazards, the cyclic process can release and rerelease contaminants into other products, workplaces, and environments. The functions of the ecosystems may be compromised by persistent organic pollutants, heavy metals, and some additives that impact species survival, reproduction, and trophic relationships, and downstream the functions of the ecosystems; pollination, fisheries productivity, and water quality regulation [46,47].

Circularity does not necessarily imply the risk of toxic circularity; only in the form of circularity without material overall control. The decision of product design, disclosure of chemicals, sorting technologies, and regulatory standards can make or break cycling, whether safe or harmful[48]. This means that non-toxicity goals and traceability channels, which inhibit hazardous loops, have to be integrated with circular approaches, on a mechanism-based approach. In the absence of this form of coupling, circularity might augment ecological risk, although it enhances mass-based recycling indicators.

3.6. Bio-Based Circularity, Land Competition, and Biogeochemical Feedbacks

The composting, anaerobic digestion, nutrient recovery, and bio-based materials are typically placed as synergistic with the ecosystem services because they have the potential to improve soil organic matter, enhance nutrient cycling, and lead to carbon sequestration when used in a due manner[49]. These strategies can reinforce supporting services that support agricultural productivity and regulate services related to water retention and erosion control by putting organic matter back into soils. In other backgrounds, they alleviate uncontrolled emissions of methane out of unmanaged organic debris, which aids in regulating the climate.

On a big scale, bio-based circularity, however, creates a land competition/biogeochemical feedback mechanism[50]. Higher biomass demand may encourage agriculturally intensive production or land use, which may have unfavorable consequences for habitat integrity, water management, and carbon storage. There is also a danger of leakage due to nutrient recovery in case the rates of application exceed ecological assimilation rates and contribute to eutrophication and loss of aquatic regulating services. The nature of these trade-offs will be based on the source of feedstock, land governance, agronomic activities, and whether the biomass is sourced based on residual or dedicated crops[51]. The mechanism thus validates the necessity of threshold-cognizant planning, which correlates the circular growth of the bioeconomy to landscape carrying capacity and a safeguard of biodiversity.

3.7. System Reconfiguration, Connectivity, and Cross-Scale Effects

The implementation of the circular economy is more than a combination of individual technical interventions, but can also represent a reconfigured system that changes the infrastructure, connectivity, and spatial order[52]. One example of such industrial symbiosis is associated with firms that exchange by-products, energy, and water, which could help to reduce the amount of waste and primary resource use. The reconstruction of the material flows is possible in circular cities due to constructing material reuse, decentralized waste processing, and the increased recovery of resources. When these changes help to reduce pollutant loads, minimize extraction pressures, and allow making investments in green and blue infrastructure focused on enhancing urban heat regulation, flood reduction, and recreational services, they can introduce ecosystem service co-benefits.

This mechanism is based on cross-scale effects. The reconfigurations at the city/regional levels can change the pressures towards the upstream and downstream levels, which can alter the location of the ecosystem service impacts[53]. Reverse supply chain logistics systems have the capacity to add transport emissions, land use requirements of hubs, whereas decentralizing processing can decrease long-haul transport but amass localized emissions foci. The degree to which reconfiguring the systems can result in net ecosystem service achievements rests upon the ability to get the jurisdictions to cooperate, align land and water planning, and entrench ecological priorities into industrial and urban design. In the absence of such alignment, a spatially-based infrastructure may accidentally become entrenched in circular patterns that exacerbate ecological pressure in the long run.

3.8. Implications of Mechanism-Based Understanding for Sustainable Resource Management

The explanation of a mechanism-based interpretation makes it clear that the relationship between the CE and ES is not uniformly positive, and explaining it as conditional and context-dependent makes more sense[54]. Circular strategies have the potential to minimize the extraction and pollution, which would contribute to the integrity of ecosystem services, but they may also present new demands due to reinforced processing, cycling of hazardous materials, and competition for land. The desired interplay between technology, energy systems, governance, spatial planning, and ecological vulnerability creates the net effect[55]. This means that management of sustainable resources demands assessment structures that monitor the locations where pressures are alleviated, where they are highly fixed, and how ecosystems react over both time and levels.

This reasoning, based on mechanisms, also forms the basis of reasoning in the subsequent sections that will be focused on synthesis, as identifying what is supposed to be monitored and controlled when it comes to realistically applying the circular transitions. It focuses on the material composition and material toxicity, location and control of processing plants, magnitude, and procurement of biomass, and trade-off effects. Above all, it connects the goals of circularity and ecosystem condition and resilience, establishing a channel to shift the goals of circularity toward regenerative results that secure and improve ecosystem services. The principal mechanisms linking circular interventions to ecosystem service outcomes are summarized in **Table 2**[24]. This table shows the effect that individual CE activities (e.g., recycling, reuse, nutrient recovery) have on environmental pressures (e.g., material extraction, emissions, and land use). These pressures influence the conditions of an ecosystem, such as soil fertility, water quality, and biodiversity, and eventually dictate the service delivery of the ecosystem.

Table 2. Mechanisms through which circular economy interventions influence ecosystem services along the pressure-condition-service chain.

Mechanism (CE → Pressure Pathway)	What Changes in Ecosystems (Condition)	Ecosystem Services Likely Affected	Directionality Notes	What to Measure (Examples)
Avoided virgin extraction	Reduced habitat disturbance; lower sediment/acid drainage risk	Habitat-related services, water regulation, cultural landscape values	Benefits depend on substitution and location of avoided extraction	Virgin material displacement; land-use change in extraction regions; watershed sediment load
Reduced waste leakage	Lower debris and contaminant loads	Water purification, fisheries productivity, recreation	Strong where leakage is currently high	Mismanaged waste rates; plastic leakage; coastal/river debris indices
Increased reprocessing intensity	Higher local emissions/residues; water use	Air quality regulation, water purification, local amenity	Can create localized ES losses even if global extraction falls	Facility-level emissions; effluent loads; energy/water per ton processed
Toxic circularity	Persistent contaminants redistributed across cycles	Biodiversity-dependent services, water purification, soil function	Risk grows with complex materials/additives	Chemical composition/traceability; contaminant concentrations; toxicity indicators
Bio-based expansion/competition	Land conversion; altered hydrology; nutrient cycling shifts	Carbon storage, flood mitigation, pollination, soil fertility	Outcomes hinge on feedstock and governance	Land demand; nutrient balances; soil organic carbon; habitat fragmentation
Reverse logistics expansion	More transport emissions; land for hubs	Climate regulation; local air regulation	Depends on network design and energy system	Transport-km; fuel mix; siting proximity to sensitive ecosystems
Restoration co-benefits (when coupled with nature-based solutions)	Improved green–blue infrastructure; higher resilience	Heat mitigation, flood regulation, recreation/cultural services	Strongest in cities/watersheds with coordinated planning	Green cover; infiltration capacity; temperature/flood risk metrics; access indicators

4. Synthesis of Evidence by Circular Economy Strategy

The evidence linking circular economy strategies to ecosystem service outcomes is heterogeneous in scope, methods, and spatial coverage, yet several consistent patterns emerge when studies are organized by the type of circular intervention. Across strategies, the direction and magnitude of ecosystem service effects depend on substitution effectiveness (whether secondary or life-extended options truly displace virgin production), process burdens (energy, water, residues, and emissions associated with circular activities), and the governance context that determines material safety, siting, and landscape constraints[56]. This section synthesizes the literature by major circular strategy families and interprets results through the pressure–condition–service framing established earlier. Rather than treating circularity as inherently beneficial, the synthesis emphasizes the conditions under which circular interventions deliver credible ecosystem service gains, as well as recurring trade-offs that can undermine ecological integrity.

4.1. Demand-Side and Design Strategies: Refusing, Rethinking, and Reducing

Demand-side and design-oriented strategies are frequently associated with the most robust ecosystem service co-benefits because they aim to prevent resource use and waste generation upstream. Interventions such as dematerialization, lightweighting, product-as-a-service models, shared use, and design for durability reduce demand for virgin inputs and can therefore decrease extraction pressures that damage habitats and disrupt hydrological and biogeochemical processes [57]. In conceptual and modeling studies, these strategies are often linked to broad improvements in regulating services, especially climate regulation through reduced emissions and carbon loss, and supporting services through reduced land conversion and pollution loading.

Empirical evidence, however, suggests that realized ecosystem service benefits are contingent on behavioral and market responses [58]. Rebound effects can erode gains if efficiency improvements lower costs and increase consumption, or if sharing platforms stimulate additional travel and associated emissions. Similarly, design changes that reduce material mass can increase reliance on composite materials or chemical additives that complicate end-of-life management, introducing risks of toxic circularity or reduced recyclability. The literature therefore suggests that the ecosystem service advantages of demand-side strategies are strongest when interventions are coupled with policies that cap or redirect demand, ensure non-toxic material design, and align business incentives with absolute reductions in throughput rather than relative efficiency alone [59].

4.2. Product Life Extension: Reuse, Repair, Refurbishment, and Remanufacturing

Life extension strategies often show favorable environmental performance in life cycle studies because they preserve embedded material and energy value and reduce the need for new production [60]. When substitution holds the meaning that each additional year of use displaces the manufacture of a new product, these strategies can reduce upstream extraction and associated land-use impacts, with implications for habitat-related services, water regulation, and climate regulation. In sectors such as electronics, appliances, and certain vehicle components, remanufacturing and refurbishment have been framed as particularly promising because they can retain high-value components and reduce virgin material demand for energy-intensive manufacturing [61].

Ecosystem service outcomes nevertheless vary with product type, technology change rates, and infrastructure requirements. For rapidly improving technologies, extending the life of less efficient products can increase energy consumption and associated emissions, potentially weakening climate regulation benefits, especially where electricity grids remain carbon-intensive. In addition, older products can contain hazardous substances that are restricted in newer designs; prolonged use and informal repair can increase exposure risks and complicate controlled end-of-life treatment, with downstream consequences for soil and water purification services if leakage occurs. The evidence suggests that life extension strategies are most likely to yield net ecosystem service benefits when accompanied by safe materials management, high-quality repair and remanufacturing standards, and energy system decarbonization that reduces operational trade-offs [30,62].

4.3. Recycling and Recovery: Closing Loops under Process and Toxicity Constraints

Recycling is the most prominent and widely implemented circular strategy, and it is often assumed to deliver ecosystem service benefits by displacing virgin extraction and reducing waste disposal [63]. Many studies support this general mechanism, particularly for metals and some construction materials, where secondary production can significantly reduce energy use and mining burdens. Avoided extraction can protect habitats and reduce water pollution associated with mining and ore processing, contributing to regulating services and, in some contexts, improving cultural services tied to landscape integrity.

Meanwhile, recycling evidence base continuously mentions the limitations that define whether circularity will result in ecological benefits [18]. To begin with, recycling may be both energy and water-consuming and may also produce concentrated emissions and wastes left behind. Such local effects may undermine the quality of air and water management in the areas surrounding the processing sites, particularly the poor regulation of pollution in the visitation of facilities and clustering facilities in areas of sensitive ecosystems. Second, the substitution may be restricted by the material quality loss and contamination under the assumption that higher recycling rates do not result in a decrease in virgin production, when the recycled materials are further downcycled into lower-grade uses. Third, and as it is becoming more dominant in the literature, is the question of dangerous additives and mixed material products. In materials streams with long-lingering or toxicant substances, heightened recycling has the potential to augment the risk of contaminant redistribution through products and atmosphere and hazard ecosystem processes insufficient to sustain biodiversity, pollination, fisheries and water purification. Such evidence implies a change that is not more recycling but safe and high-quality recycling with a focus on design to be recyclable, full chemical disclosure and recycling governance systems to avoid toxic loops[64].

4.4. Bio-Based Circularity and Nutrient Loops: Potential for Synergy with Ecosystem Functioning

The bio-based circular approaches have one of the unique positions in the literature since they could have direct communication with ecological mechanisms. Organic waste composting, anaerobic digestion, digestate management, retrieval of nutrients in wastewater, and biochar amendments are often associated with improvement in soil structure, nutrient retention, and carbon storage functions to support provisioning services such as crop production and regulating services such as climate control and water control. In farming settings, when the organic matter is returned to the soil, resilience to drought and erosion could be strengthened, and there is a possibility that climate variability will increase the stability of flows of ecosystem services[65].

There are also indications of tremendous trade-offs and context sensitivity[24]. The positive impacts of nutrient cycling are conditional on the prudent association between nutrient application and ecological assimilative capacity; nutrient leakage may aggravate eutrophication and jeopardize biodiversity in the freshwater and coastal ecosystems in terms of water cleansing, fishery business, and recreation. Furthermore, by increasing bio-based circularity via increased production of biomass, land-use pressure can be exacerbated, endangering the integrity of habitat and carbon stocks when it encourages land conversion. Bio-based materials and bioenergy pathways studies frequently focus on the fact that results will be determined by the source of feedstock, and resourcing systems based on residues may also have fewer land-use competing demands compared to the cycling systems that depend on specific crops. In general, the literature indicates that bio-based circularity may be aligned with ecosystem service improvement strongly when planned within the landscape and biodiversity protection, and provided with confirmed net tangible positive changes in soil and water functions[49].

4.5. System-Scale Configurations: Industrial Symbiosis, Circular Cities, and Urban Mining

Circular plans at system scale seek to restructure material movements between companies, industries, and cities, which may provide significant aggregate waste and virgin resource cuts. Industrial symbiosis can optimize emissions and waste by the exchange of by-products and common utilities and bills pair capable of integrating loops of construction materials, the decentralization of resource recovery, and the green-blue infrastructure investment. Urban mining, the extraction of metals and material resources out of buildings, infrastructure, and waste stocks, has been put against a backdrop as a strategy to mitigate new extraction pressures and supply risks due to the lack of vital materials[66].

The ecosystem service implications of system-scale circularity are mediated by coordination and spatial planning[24]. When circular reconfiguration reduces landfill dependence and unmanaged waste leakage, it can improve local regulating services, particularly water quality and disease regulation. When coupled with nature-based solutions and land-use planning, circular city initiatives can strengthen urban heat regulation, flood mitigation, and cultural services through enhanced green space and restored waterways. However, the evidence also warns of infrastructure lock-in and burden redistribution. Reverse logistics networks, processing hubs, and industrial clustering can concentrate environmental burdens, with potential impacts on nearby ecosystems and communities. The ecosystem service performance of system-scale strategies, therefore, depends on governance capacity, siting decisions, and the integration of ecological thresholds into planning processes rather than on circularity ambitions alone[30].

4.6. Cross-Cutting Patterns and Conditions for Ecosystem Service Gains

Across the strategy families, several cross-cutting findings recur. First, strategies that avoid material use and production upstream tend to show the most consistent potential for broad ecosystem service improvements because they reduce multiple pressures simultaneously. Second, substitution is decisive: circular activities generate ecosystem service benefits only when they meaningfully displace virgin extraction and linear production, rather than adding parallel streams. Third, toxicity and material complexity shape outcomes; without safe materials design and traceability, closing loops can intensify ecological risk. Fourth, spatial distribution matters; aggregate benefits can coexist with localized ecosystem service degradation where processing burdens are concentrated. Lastly, basic moderators are energy systems and land governance. Decarbonized energy enhances margins of ecosystem service provision to processing-intensive strategies, and sound land and water policies are required to guarantee that bio-based circularity enhances and does not diminish ecological provision[67].

Through such conditions of synthesizing the literature, the performance of a circular economy is redefined as an environmental question rather than a material one. The evidence shows that circularity would make the most promising progress in sustainable resource management in cases where it is motivated as a way of alleviating pressures on ecological boundaries by using suitable governance measures which facilitate a safe cycle, avoid lack of displacement, and adjust circular interventions to the preservation and recovery of ecological services[68].

5. Sectoral Pathways for Sustainable Resource Management

Sectoral context strongly shapes how circular economy interventions translate into ecosystem service outcomes because sectors differ in their dominant material stocks and flows, their pollutant profiles, their land and water footprints, and the ecological settings in which impacts occur[24,69]. The same circular strategy can therefore generate very different ecosystem service effects depending on whether it is applied in agriculture, the built environment, chemicals, electronics, or water systems. In addition, sectoral supply chains operate across multiple spatial scales, linking local ecosystems to global extraction frontiers and transboundary pollution pathways. This section synthesizes the literature through a sectoral lens to clarify which intervention types appear most influential, which ecosystem services are most affected, and which enabling conditions determine whether circular transitions support sustainable resource management. The way that the approaches of the circular economy work varies by economic sector, and its environmental impacts are subject to sector-specific flows of resources and environmental stress (**Figure 2**). **Table 3** summarizes the sector-specific implications of the interventions of a circular economy with regard to ecosystem services and their trade-offs. The table provides the identification of common circular strategies in industries like agriculture, construction, plastics, electronics, and water systems, and shows the ecosystem service benefits and trade-offs. The circular economy strategies are working in varied economic sectors, and the sectors have varied flows of resources, environmental strain, and dependence on ecosystem services[18].

The concept of the circular economy has also been implemented in various industries, indicating its high level of applicability in enhancing the performance of the ecosystem services, as well as promoting the creation of sustainable resource management. Nutrient recycling, composting of organic waste, and regenerative agricultural methods are examples of agri-food systems with circular methods that can be used to enhance soil fertility, improve water infiltration, and lessen the use of synthetic fertilizers, thus contributing to the regulation and provisioning of ecosystem services[70]. In the built environment, strategies such as the reuse of materials, design conducive to disassembly, and circular construction methods can diminish the exploitation of raw materials and waste in construction, as well as decrease environmental impacts on land and other natural resources[71]. Circular interventions in the plastics and textiles industries include recycling, replacement of materials, and the life cycle of the products, to minimize waste formation and pollution, which jeopardize terrestrial and marine ecosystems[72]. Likewise, circular approaches in the electronics industry, including repair, refurbishment, and responsible e-waste management, can lessen the environmental impact of toxic substances and manufacturing processes that demand a lot of resources[61]. In the minerals and critical materials industry, enhanced material recovery and urban mining can serve to curb the environmental effects of primary mining operations, which, in most cases, are associated with damage to habitats, water pollution, and loss of biodiversity[73]. Lastly, circular water systems, i.e., wastewater reuse, nutrient recovery, and integrated water resource management, can improve water availability and ecosystem health, as well as decrease loads of pollution entering aquatic ecosystems[74]. Collectively, these sectoral applications demonstrate the role of sectoral approaches to the circular economy in supporting and delivering ecosystem services within a variety of resource systems, and they also point to the importance of implementing circular economy approaches contextually to prevent the emergence of unwanted environmental trade-offs.

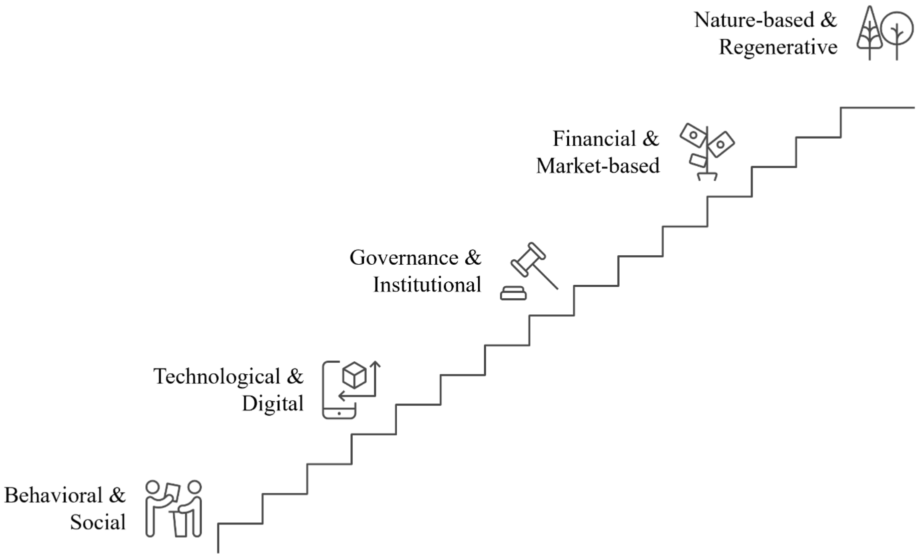

Figure 2. Circular economy intervention overview of major sectors.

Note: The major sectors, such as agri-food systems, built environment, plastics and chemicals, electronics, and water systems, and their possible ecosystem service implications with emphasis on the environmental and sector-specific trade-offs.

Table 3. Sectoral synthesis: Interventions, affected ecosystem services, and dominant trade-offs.

Sector	Dominant Circular Interventions	Key Ecosystem Services Influenced	Typical Co-Benefits	Recurrent Trade-Offs/Risks	Enabling Conditions for Net ES Gains
Agri-food	Nutrient recovery, composting/Anaerobic Digestion (AD), food waste prevention	Soil fertility, water purification, climate regulation, pollination	Improved soil function; reduced landfill methane; lower upstream land pressure (via waste reduction)	Nutrient leakage/eutrophication; land competition for biomass	Nutrient budgeting at watershed scale; residue-based feedstocks; enforcement on runoff
Built environment	Design for disassembly, reuse of components, high-value recycling	Habitat integrity (via avoided quarrying), flood mitigation, urban heat regulation, cultural services	Reduced extraction; less landfill; improved urban resilience with green–blue infrastructure	Siting burdens from processing; contamination in legacy materials	Spatial planning + emissions control; material passports; safe handling standards
Plastics/ textiles/ chemicals	Reuse/refill, safer design, improved collection + recycling	Water quality, recreation/amenity, biodiversity-dependent services	Reduced leakage; potential lower upstream water/land footprints (textiles)	Toxic additives; microplastics/microfibers; downcycling	Chemical transparency; prevention at source; quality standards for safe recycling
Electronics/ critical minerals	Repair/refurbish, modularity, take-back, advanced recycling	Habitat preservation (via avoided mining), water regulation, cultural landscape values	Reduced extraction pressure; supply security	Informal recycling pollution; complex material streams limit recovery	Design for disassembly; controlled recycling; Extended Producer Responsibility (EPR) and enforcement
Water/ wastewater	Reuse, nutrient/energy recovery, decentralized treatment	Water purification, disease regulation, freshwater provisioning	Reduced nutrient loads; improved resilience in water-scarce regions	Altered ecological flows; brine/residual disposal issues	Ecological flow requirements; integrated watershed management; safe residual handling

5.1. Agri-Food Systems: Nutrient Cycling, Soil Function, and Landscape Resilience

Agri-food systems are central to the CE ecosystem service nexus because they both depend on and directly modify ecosystem functions[75]. Circular interventions in this sector often focus on closing nutrient loops through manure management, composting, anaerobic digestion, phosphorus recovery from wastewater, and the redistribution of organic residues to soils. Where these interventions are well-governed and aligned with local assimilative capacity, the evidence indicates potential improvements in supporting services such as soil formation and nutrient cycling, alongside regulating services such as water regulation and climate regulation through enhanced soil organic carbon and reduced methane emissions from unmanaged wastes. In addition, reductions in food loss and waste can lower the upstream land and water demands of food production, indirectly supporting habitat integrity and biodiversity-dependent services such as pollination.

Simultaneously, the literature is consistent in pointing out that circular nutrient strategies are extremely prone to spatial disconnect between nutrient producers and sinks[76,77]. Even when nutrients are recovered, concentrated livestock production has the potential to produce surpluses of nutrients that overwhelm on-site ecosystems, leading to runoff, eutrophication and loss of freshwater and coastal ecosystem services, such as water purification, fisheries productivity and recreation. Circularity efforts can therefore fail to deliver ecosystem service gains if they increase the circulation of nutrients without resolving underlying structural drivers of nutrient overload. Moreover, bio-based circularity can increase competition for land and biomass, particularly when residues are diverted to industrial uses or when dedicated energy or material crops expand. These dynamics can reduce regulating services linked to carbon storage and flood mitigation if land conversion occurs, and can undermine biodiversity-dependent services if habitat simplification intensifies. Overall, evidence suggests that agri-food circularity supports ecosystem services most reliably when nutrient recovery is coupled with land-use governance, regionally coordinated nutrient budgeting, and practices that improve soil function while protecting aquatic ecosystems from leakage[78]. Real-world implementations of circular strategies demonstrate that ecosystem service outcomes can vary considerably, with both beneficial and adverse effects observed depending on context and governance arrangements (**Figure 3**).

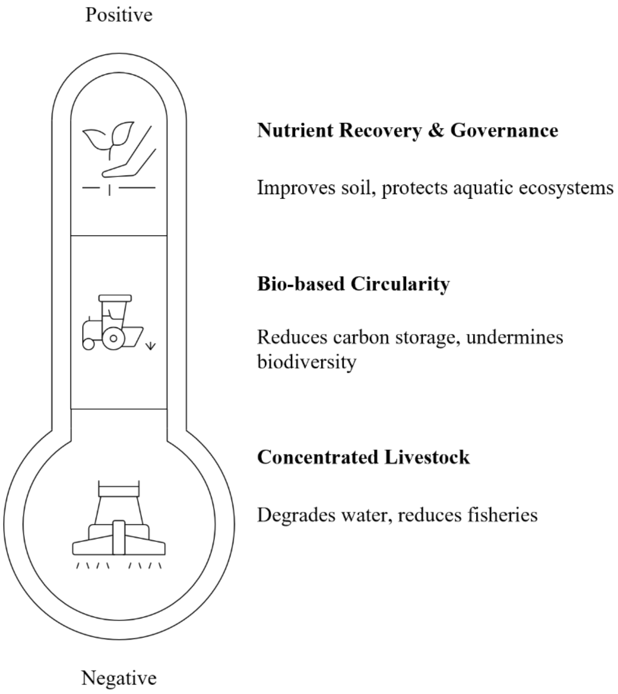

Figure 3. Theoretical example of case studies of the positive and negative ecosystem service impacts of circular economy interventions, with a particular focus on system design, governance, and ecological constraints.

5.2. Built Environment and Cities: Material Stocks, Urban Metabolism, and Multifunctional Ecosystems

The built environment contains some of the largest material stocks in modern economies, and circular strategies in this sector, such as construction material reuse, design for disassembly, modular building, high-quality recycling of aggregates and metals, and the extension of building lifetimes, are often linked to substantial reductions in primary extraction of sand, gravel, timber, and metals[79]. By reducing demand for virgin construction materials, circular construction can lessen upstream impacts from quarrying, mining, and logging that degrade habitat quality and disrupt water regulation. In urban settings, circular city agendas frequently connect material loops with resource-efficient infrastructure and nature-based solutions, creating pathways to enhance regulating services such as heat mitigation, stormwater retention, and air quality regulation, as well as cultural services linked to recreation and urban well-being[80].

It is also in the evidence base of critical trade-offs. The concentration of reprocessing activities, demolition waste treatment, and transport flows on urban circularity can increase the pollution liability in the area of focus and decrease the quality of ecosystem services in the area in case the facilities are located close to waterways or green areas without sufficient protective measures. Besides this, cyclic construction performance requires management of contamination in older materials; old buildings have hazardous materials, which can make it complicated to reuse and recycle materials and may pose threats to the properties of soil and water in the event that such hazardous materials are not treated. One of the common findings is that the ecosystem service performance of circular strategies in the built environment is better when circular design is combined with spatial planning that unambiguously recognizes the importance of urban and peri-urban ecosystems, takes into account redevelopment as well as the watershed, and invests in green-blue infrastructure delivering more than material efficiency [81].

5.3. Plastics, Chemicals, and Textiles: Circularity under Toxicity and Leakage Constraints

The idea of circular transitions of plastics, chemicals, and textiles is often discussed as a way to prevent leakage and pollution of waste and especially in the marine and freshwater systems whose environment can be impacted by plastic debris and microplastics [82]. Recycling schemes, refill schemes, collection optimization, and better recycling can be used to minimize litter and landfill loads, which can be used to manage regulating services to do with water quality and cultural services to do with recreation and aesthetics. In the textile sector, circular approaches such as repair, resale, fiber-to-fiber recycling, and more lasting design can decrease upstream water and land pressure in locales connected with cotton farming and synthetic fiber making, and may have a prospective effect on water management and services connected with habitat.

Nevertheless, the literature pays the greatest attention to this area, which is also where the difference between circularity and ecological safety should be highlighted. The numerous polymer and textile products are loaded with additives, dyes, and finishing chemicals, which may make it challenging to recycle materials and may even cause the occurrence of contamination between cycles. This is a hazard other than the fact that circularity will not actually decrease harm, but it will redistribute the hazardous substances in a new product and in new environments, compromising the services of the ecosystem through chronic toxicity and bioaccumulation. Furthermore, even extremely circular systems can fail to stop leakage in case of an incomplete collection, informal waste management is still active, or the microfibers and microplastics are still leaching during use. The argument is that ecosystem service benefits in these areas are based on upstream design measures that minimize the toxic chemical complexity, on traceability and standards that facilitate the provision of safe recycling opportunities, and on preventive measures of reducing plastic and microfiber release at the source as opposed to end-of-life solutions [83,84].

5.4. Electronics and Critical Minerals: Urban Mining, Displacement, and Biodiversity Risks

Electronics and other high-tech sectors are increasingly central to resource governance because they depend on critical minerals with high extraction impacts and supply risks. Circular strategies such as repair, refurbishment, modular design, take-back systems, and advanced recycling are often linked to reduced demand for virgin mining and to improved security of supply [85]. Where effective, these strategies can yield ecosystem service benefits by avoiding extraction-driven habitat destruction, water contamination, and social–ecological disruption in mining regions. Urban mining and the recovery of metals from end-of-life products are frequently framed as pathways to reduce pressure on high-biodiversity extraction frontiers, thereby supporting regulating services and biodiversity-dependent functions.

However, the facts point to some limitations that restrict these advantages. The complex design of the product, speedy shift in technology, and streams of mixed materials may limit recovery rates and diminish substitution efficiency. Informal recycling may result in sharp local pollution, such as the emission of heavy metals and persistent organic pollutants, the degradation of water purification, water air regulation, and human health [86]. Even formal recycling may result in residues that need to be taken care of. Besides, circular gains can be counterbalanced through greater demand for electronics and energy transition technologies, and hence, circularity will not reverse but rather halve the growth of extraction pressure. The literature hence underlines that what is needed in terms of improving ecosystem services in this sector is centered on design to dismantle, eradication of harmful additives, safe recycling standards, and policies that take into consideration the increase in consumption and the implementation of circular supply [82].

5.5. Water and Wastewater Systems: Circular Water, Nutrient Recovery, and Watershed Services

The example of water systems explains how human economies are directly reliant on the ecosystem services, especially the freshwater provisioning, purification services, and flood and drought regulation services. Circular approaches to this industry are water reuse, harvesting resources out of the wastewater (nutrients, energy, heat), and decentralized methods of treatment, which can minimize the release of pollutants and allow more effective utilization of water. It is hinted that wastewater treatment and recovery of resources could enhance the regulating services by decreasing the extent of nutrients and pathogens to the rivers, lakes, and coastal areas, and sustain the water quality, fisheries, and recreational services [87]. Reuse, in water-scarce areas, may decrease pressure on overdrawn aquifers and river systems and could be useful in providing ecosystem health when withdrawals decrease. Trade-offs arise when circular water initiatives are pursued without sufficient watershed-scale coordination. Water reuse can alter downstream flow regimes, potentially affecting habitats and the ecosystems that rely on return flows, with implications for regulating and cultural services. Concentrated brines or residuals from advanced treatment can create localized disposal challenges. Nutrient recovery can reduce discharges, but, as in agri-food systems, the ecosystem service outcome depends on how recovered nutrients are applied and whether they increase or decrease net nutrient loading in sensitive catchments. The literature therefore suggests that circular water strategies deliver the strongest ecosystem service co-benefits when implemented as part of integrated water resource management that accounts for ecological flow needs, cumulative pollutant loads, and the spatial distribution of costs and benefits across communities [78,88].

5.6. Cross-Sector Insights for Sustainable Resource Management

Across sectors, several generalizable insights emerge about how circular economy pathways can advance sustainable resource management through ecosystem services. First, the strongest and most consistent ecosystem service co-benefits tend to occur where circular interventions reduce upstream pressures on land conversion and extraction and where substitution is demonstrably effective. Second, sectors characterized by complex material chemistry and diffuse leakage pathways require a stronger focus on prevention, safe material design, and governance of hazardous substances; in these contexts, circularity metrics can be misleading if they obscure toxic or micro-pollutant burdens. Third, localized concentration of burdens is a frequent hazard in any area with an expansion of circular processing infrastructure, which makes the significance of the location choice, emissions regulation, and equity among the environment even more emphasized. Fourth, land and water governance are the so-called master variables of bio-based and water-related circularity. Without landscape and watershed controls, the circular initiatives can lead to increasingly strong pressures that diminish the quality of regulating services. Lastly, sectoral transitions are linked: electrification and digitalization can push the burden onto the mining and energy systems, and decarbonization can increase the net productivity of processing-intensive circular strategies to the ecosystem services. Such interdependencies suggest that the policies of the circular economy can be coordinated with biodiversity conservation, watershed management, and climate policies, so that the circularity of the sector leads to the sustainable ecosystem services benefits instead of the ecological displacement and costs shifting to the ecosystems [24,89,90].

6. Limitations and Future Directions

Although there is a sudden surge in the amount of scholarship at the intersection of circular economy and ecosystem services, the area has been limited by conceptual, methodological, and empirical constraints that make synthesis a difficult endeavor and limit the range of decisions. The most common problem is that most works use circularity as a proxy concept of sustainability, excusing an augmented recirculation, a rise in recycling rates, or a fall in waste, as details enough on the well-being of the environment[91]. However, ecosystem services become necessary upon ecosystem condition, resilience, and spatially explicit ecological processes, which can even fall behind, or worse still, decline, under specific circular transitions. The literature, thus, is composed of authentic evidence of co-benefits as well as a broad amount of literature where the outcome of ecosystem service is conjectured, and not proved. The importance of identifying these shortcomings is not only one of scholarly rigor but an indispensable part and parcel of a circular policy as well as business strategy that unknowingly leads to the increment of the ecological degradation in the name of efficiency when it comes to resources.

6.1. Conceptual and Definitional Limitations

The absence of standardization of concepts around the meaning of a successful circular economy and the ecological interpretation of said success is one of the essential limitations. The interventions that are described as circular economy include such things as recycling efforts, circular procurement, industrial symbiosis, bio-based materials, and dematerialized service models[8]. These interventions differ in their regimes of pressure and in their probable ecosystem service impacts, but research commonly compares them using one term of circularity. The frameworks of ecosystem services are also diverse, with typologies taking on different facets of ecological liability and human prosperity, and the value systems have varying importance on the ecological service. Consequently, there are occasions when findings cannot be compared across the research studies, though they may be dealing with different areas or interventions.

The other conceptual restriction is the boundaries of systems. Circularity is commonly measured at the product or supply-chain scale, where it cannot reflect the displacement impacts, i.e., extraction to new jurisdictions, land-use change under bio-based demand, and waste and residue export to less protective jurisdictions[92]. Such boundary decisions are particularly sensitive to ecosystem service effects since service locations are spatial, and ecological damages may be clustered at certain locations in the face of downward material footprint aggregations. Furthermore, temporal framing of most research overstates ecological time lags and the temporal profile of potential threshold behavior, resulting in quality conclusions that can be over-optimistic in the short-term, but not in the long-term ecological stability in terms of ecosystem service delivery.

6.2. Indicator Mismatch and the Challenge of Measuring Ecosystem Service Outcomes

The second weakness is a constant indicator mismatch. The research on circular economy often uses the metrics that are easily accessible, including the rates of recycling, the figure of material circularity, the rate of waste diversion, and the portion of the secondary inputs[25,93]. These indicators are informative relating to material flows, but cannot quantify the state of the ecosystem or the provision of services. Instead, ecosystem services can be quantified by biophysical measures or ecological models, or proxy measures like land-use change or generic biodiversity measures. Correspondences between indicators of circularity and ecosystem service outcomes are thus indirect and, in most cases, feeble[94].

There are a number of effects associated with this mismatch. First, research can exaggerate ecosystem services by suggesting that the decreased flow of materials will be converted to ecological gains without quantifying the change in the quality of the habitats, hydrological services, and the level of pollutant loads at an ecologically relevant scale. Second, biodiversity and ecosystem services are occasionally measured using coarse proxies that fail to capture the processes that may cause the largest impact on circular transitions, including toxic cycling, release of micro-pollutants, or concentration of burden around reprocessing plants. Third, cultural service and distributional variables of service provision are especially poorly represented since they are challenging to measure and frequently omitted in the general circularity measurements. These loopholes limit the capability of research to guide the formulation of policies that would ensure the ecological integrity is preserved, as well as safeguard the social well-being[95].

6.3. Methodological Limitations: Scale, Causality, and Uncertainty

Methodological challenges arise from the multi-scale nature of the CE–ES relationship and from the difficulty of causal attribution. Many circular interventions are implemented at product, firm, or municipal scales, while ecosystem services are shaped by landscape and watershed processes[24]. Linking the two requires approaches that can represent both supply-chain dynamics and spatial ecology, yet most studies employ tools optimized for one domain. Life cycle assessment can represent upstream and downstream burdens, but often struggles with spatially explicit ecosystem service modeling and non-linear ecological responses. Ecosystem service models can represent spatial variation but may not capture global supply-chain displacement or market-mediated responses. Input–output approaches can represent displacement across regions, but can be coarse regarding ecological mechanisms and local ecosystem vulnerability[96].

The other limitation is causality. The circular nature of ecosystems means that changes in the ecosystem condition or service delivery are seldom due to circular interventions alone, since there are several other drivers, such as climate variability, land management, infrastructure development, and policy change, that affect ecosystems[97]. It may prove challenging to confound the added effect of circular strategies on ecosystem services without a strong counterfactual, longitudinal monitoring, or quasi-experimental design. The uncertainty is also sometimes not reported. Due to ecosystem reaction sensitivity to domestic situations and the ambiguity in projecting adoption, substitution, and rebound, plausible synthesis may entail explicit description of uncertainty, sensitivity modelling, and clear presentation of important assumptions.

6.4. Data Gaps and Uneven Empirical Coverage

Empirical studies have been skewed regarding location, industry, and categories of ecosystem services. The studies are focused on some well-off settings and in areas where there is easier availability of data, like in municipal waste management or specific industrial symbiosis networks. In contrast, circular transitions in the informal economies, transboundary trade in secondary materials, and regions with both highly valuable and highly vulnerable ecosystem services have less evidence. In terms of sector, less of the high-resolution literature on circularity as a connector of ecosystem services to complex chemical product systems, textiles, and highly dynamic electronics provision systems, in which toxicity and complex material structures are main elements, has been made. Within ecosystem service categories, most categories of services, e.g., climate regulation, are frequently controlled, whereas less represented or omitted ecosystem services include cultural services and biodiversity-dependent services[98].

These gaps matter because circular economy policy and investment are expanding globally, including in contexts where governance capacity, enforcement, and infrastructure differ markedly from those in which most evidence has been generated[99]. Without broader empirical coverage, there is a risk that best practices inferred from well-regulated settings will not generalize to places where processing burdens, leakage, or informal recycling dominate, potentially producing ecosystem service losses even as circularity metrics improve.

6.5. Governance and Equity Limitations

Many studies acknowledge governance as important but treat it as a background variable rather than a central determinant of outcomes. Yet governance shapes the ecosystem service consequences of circular transitions through chemical regulation, extended producer responsibility, siting and permitting decisions, land-use planning, and enforcement of emissions standards[24,100]. It also determines how costs and benefits are distributed. Circular strategies can shift environmental burdens toward communities located near recycling and processing facilities, and can affect access to ecosystem services through changes in land and water use. Equity considerations are therefore not ancillary; they are part of the mechanism by which circular transitions succeed or fail socially and ecologically. The literature still lacks sufficient integration of environmental justice perspectives, participatory governance, and distributional analysis into CE–ES assessments, limiting the ability to evaluate whether circular transitions are not only environmentally sound but also socially legitimate and durable.

6.6. Future Directions: Toward Integrated, Threshold-Aware, and Decision-Relevant Research

The next step in future research should be beyond correlation and proxy-based inference to adopt a method of integrated and threshold-conscious evaluation that can assist in making real-life decisions. Harmonization is one of them: the development of universal reporting conventions, defining the type of circular strategy, systems delimiting, substitution assumptions, the nature of the energy system, spaces, and indicators of the ecosystem services applied[101]. These conventions would enhance consistency amongst different studies and minimize the chances of unfortunate sustainability assertions.

Methodological integration is the second priority. Supply-chain and economy-wide tools coupled to a spatial ecosystem services model will be important to make a decision that is relevant to various features, where the approach to life cycle or material flows is matched by a watershed or landscape model, where ecosystem services are generated[102,103]. Simultaneously, studies need to progress methodologies that are more indicative of toxicity, micro-pollutants, and material complexity, as these are key entry points of how circularity can compromise ecosystem services. Scenario analysis to reflect the dynamics of adoption, rebound risks, and policy interactions should be done, where the integrated assessments should report the uncertainty in a display meaningful to decision-makers.

Another priority is the ecological thresholds and resilience. The future work should take into account the alignment between circular strategies and ecological constraints, and restoration goals, instead of considering circularity only in the relative score. These involve recognizing at-risk critical ecosystems and services, defining ecological flow needs in water-stressed basins, and noting that active restoration can be needed, plus lower pressures to maintain service flows. These types of threshold-sensitive interventions may aid in identifying the difference between the circular interventions that only slow down rates of degradation and those that promote recovery and long-term resilience[20].

The fourth priority is monitoring and data innovation. The increase in remote sensing, sensors, and digital traceability can aid in a stricter monitoring of land-use change, water quality, facility-level emission, and material composition through supply chains[104,105]. Uncertainty in determining the toxic circularity can be reduced through digital product passports, better chemical disclosure, and standardized material databases, and facilitate the more secure looping strategies. Causation evidence and adaptive governance. Causal evidence would be enhanced by longitudinal observation of ecosystem status and service provision around circular infrastructure and any reporting of these aspects to the public.

Lastly, equity and governance, as the essential elements of sustainable circular transitions, should be discussed more specifically in the future[106]. This involves distributional studies that determine who benefits and who suffers as a result of an ecosystem service, participatory studies that involve communities in priority setting in siting and design, and policy studies that can determine what governance instruments are effective in preventing leakage, containment of hazardous materials, and circularity with biodiversity and watershed goals. The combination of these dimensions would bring the field closer to a more wholesome view of what it implies that circular economy strategies can achieve in the direction of the sustainable management of resources without undermining the ecosystems within which the societies ultimately rely[8]. The key research gaps and future recommendations are summarized in **Table 4**. The table presents the methodological issues, data gaps, and governance, and suggests research and policy responses to enhance sustainability assessment and implementation. The roadmap for advancing the Circular Economy and ecosystem service research and policy integration is displayed in **Figure 4**. To overcome these weaknesses, there is a need to have a coordinated research and policy agenda, which incorporates ecological thresholds, better data systems, and interdisciplinary methods.

Table 4. Overview of research limitations and future directions for advancing the integration of circular economy and ecosystem service frameworks.

Current Limitations	**Why It Matters for CE–ES Conclusions**	**Priority Research Advance**	**Practical Policy/Management Implications**
Inconsistent system boundaries	hides leakage, rebound, and trade displacement	harmonized boundary reporting; consequential scenarios where appropriate	align CE targets with absolute pressure reductions, not only relative efficiency
Indicator mismatch (circularity ≠ ecosystem condition)	circular metrics can improve while ES declines	paired indicator sets: circularity + ES condition/flow metrics	require ES-relevant indicators in CE policy evaluation and corporate reporting

Table 4. *Cont.*

Current Limitations	Why It Matters for CE–ES Conclusions	Priority Research Advance	Practical Policy/Management Implications
Weak representation of toxicity/material complexity	enables "toxic circularity"	traceability and chemical disclosure; improved toxicity-aware assessment	safer design standards; restrict hazardous loops; enforce material passports
Limited spatial specificity	misses local burden concentration near facilities	spatially explicit coupling of supply-chain and ES models	siting rules and cumulative impact assessment for circular infrastructure
Under-captured non-linearity and thresholds	can overestimate recovery and resilience	threshold-aware targets; resilience and tipping-point sensitivity analysis	integrate ecological limits into CE planning (watersheds, habitats, carbon stocks)
Uneven geographic/sector coverage	limits generalizability	more evidence in Global South/informal systems; sector deep-dives	tailor CE policy to governance capacity; invest in safe infrastructure and monitoring
Equity not embedded	burdens/benefits distributed unevenly	justice-oriented assessment and participatory design	incorporate Environmental Justice (EJ) criteria into permitting, procurement, and CE program design

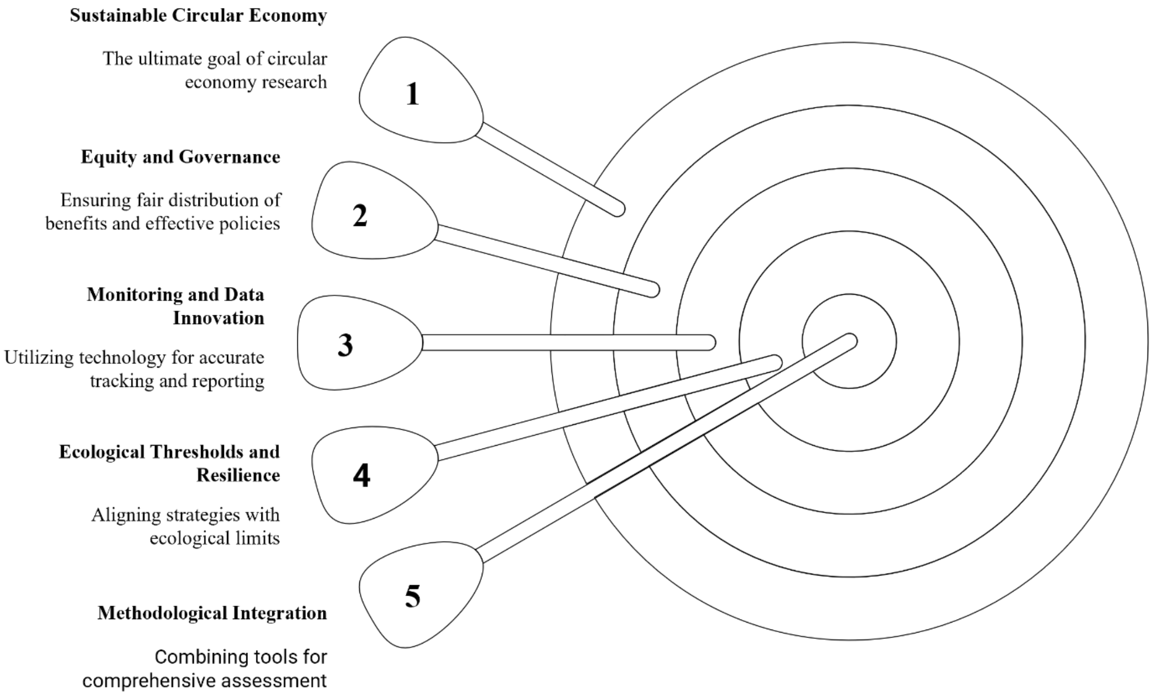

Figure 4. Conceptual roadmap on major research and policy priorities on the integration of circular economy and ecosystem service frameworks, such as the adoption of better methodologies, ecological threshold concerns, and better policy coordination.

7. Conclusion

The issue of the regional economy Circular economy has a lot of potential as a route to a more sustainable management of resources in the face of rising demands for resource depletion, climate change, and environmental destruction, which are becoming a reality throughout the world. The strategies of the circular economy are able to help reduce most of the environmental pressures that are leading to habitat loss, water pollution, and climate alteration by addressing the reduction of waste, the prolongation of product lifecycle, and the reduced necessity of acquiring virgin materials. Nevertheless, although the positive effect of circularity is often discussed in the context of highly efficient resource use and the elimination of waste, the connection between the practice of the circular economy and the service of nature is not a one-to-one relationship as it might be believed.

This review has also underscored that environmental performance of circular economy strategies is not necessarily good across the board and varies depending on a huge number of factors, such as the particular strategy used, the ecological conditions in which it is carried out, and the governance frameworks used to determine its implementation. The ecosystem service provision of circular interventions to reduce material consumption and waste could have an advantage in reducing pressures on natural resources, but may also provide new pressures or magnify existing pressures, notably where toxic materials are reused without proper controls, or where there are increases in land and water use. The circular economy should therefore be handled with a lot of caution and integrated with a clear knowledge of ecological boundaries as well as the fundamental functions that ecosystems play in human society.

Considering the cyclic element of the ecological system, to implement sustainable management of resources in the future, the concept of an ecological services system must be incorporated into the evaluation of a circular economy, such that the strategies aimed at improving the distance between material throughput, in addition to minimizing and queuing it, protect and recover the sensitive services provided by the ecosystems. Taking the perspective of how circularity is connected to ecosystem service outputs, based on recognizing synergies and the existence of trade-offs, policymakers, companies, and scientists can create interventions to promote a regenerative, as opposed to a more efficient, economy.

With the ongoing development of the domain of circular economy, the gaps in empirical data and the lack of methods, and the development of a tool of integrated assessments, which should enable the understanding of material flows and ecosystem well-being, should be bridged in future research. Research must focus on measures of ecosystem services that capture the actual realities of the ecosystem processes, and policy models must be made to establish a new circularity in the pivots of conservation of biodiversity, restoration of the ecosystem, and resilience to changes in climate.

Finally, a transition to a circular economy should not be seen as an end in itself but rather as a component of a greater change to regenerative sustainability, a transition where the economy and the ecosystems that sustain it can co-exist peacefully. Through the promotion of the circularity of systems, which consider the ecological limits and contribute to the improvement of ecosystem services, we may enter a future that will be not only resource-efficient but also ecologically resilient and socially just. By doing so, both the circular economy and ecosystem services can be effectively utilized as a potent instrument for developing sustainable resource management to ensure a healthy and resilient planet for future generations.

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Conflicts of Interest

The author declares no conflict of interest.

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