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RESEARCH ARTICLE

The Circular Space Economy: Review, Conceptualization, and Research Agenda for Narrowing, Slowing, and Closing the Loop in Orbit

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Abstract
The Space Economy (SE) is rapidly expanding, yet its reliance on a linear production and consumption model is intensifying the orbital debris problem and stands in tension with the core principles of a Circular Economy (CE). Despite increasing attention to both domains, scholarship at their intersection remains fragmented and conceptually underdeveloped, limiting cumulative theorizing on how circularity can be conceptualized in SE contexts. Addressing this gap, I conduct an integrative review of CE and SE research published between 2010 and 2025, synthesizing the contemporary literature into an organizing framework for conceptualizing the Circular Space Economy (CSE). Building on this synthesis, I advance a ten-point research agenda structured across four distinct yet interdependent pillars: (1) Orbital Property Rights and Governance; (2) Circular Ecosystems and Supply Chains; (3) Circular Business Models and Circular Product Design & Technologies; and (4) Methods and Metrics for CSE. This agenda supports future theory development and empirical research and offers a roadmap for scholars, policymakers, and industry leaders to secure the orbital environment and advance circular resource stewardship on Earth.

Keywords Circular Space Economy · Space Economy · Circular Economy · Orbital Circular Economy · Space Debris · Circular Business Model · Circular Supply Chain · Circular Ecosystem · Sustainability

1. Introduction

The philosophical foundation of Circular Economy (CE) can be traced back to the idea of *"Spaceship Earth,"* articulated in the 1960s (Boulding, 1966), which emphasizes the finite and fragile nature of resources in shared environments (cf. Paladini et al., 2021). The same decade also marked an early phase of the Space Economy (SE), then dominated by government activity (Peeters, 2021). Today, the SE has evolved into a vibrant, increasingly privatized, multibillion-dollar commercial market (cf. Crane et al., 2020) and has become essential to daily life through satellite-enabled services such as positioning, navigation, timing, and communications. Yet this growth is increasingly threatened by the rapid proliferation of satellite launches and the accumulation of orbital debris (see Figure 1), which elevates the risk of cascading collision dynamics consistent with the Kessler Syndrome (cf. Leonard & Williams, 2023). Currently, there are approximately 54,000 objects larger than 10 cm; 1.2 million smaller fragments between 1 cm and 10 cm; and 140 million particles between 1 mm and 1 cm (ESA, 2025b), and the booming commercial activities with regard to space shuttle launches (e.g., SpaceX, Blue Origin, Virgin Galactic, etc.) will further accelerate and nurture waste on earth and debris in space. At the same time, the recoverable value embedded in defunct assets and debris has been estimated at up to $1.2 trillion (Leonard & Williams, 2023), underscoring both the scale of the challenge and the potential opportunity for circular strategies in orbit.

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This is a central *puzzle*: one of Earth's most technologically advanced sectors continues to operate largely through a linear logic of production, use, and abandonment, even as it inspires innovative solutions in other domains (cf. Paravano et al., 2024). The CE has been widely adopted as an antidote to terrestrial linearity, and scholars have applied CE principles across multiple industries, including automotive (e.g., Sonar et al., 2022), defense (e.g., Reis et al., 2022), plastics and chemicals (e.g., Schultz & Reinhardt, 2022, 2023). Yet the integration of CE thinking with the SE, particularly in relation to orbital assets and debris, remains conceptually nascent. Only a small number of studies explicitly connect CE and the SE (e.g., Brennan & Vecchi, 2020; Paladini et al., 2021; Jones & Jain, 2023; Leonard & Williams, 2023). Exemplarily, this emerging Circular Space Economy (CSE) discourse acknowledges space's necessity for closed-loop systems (e.g., the ESA-MELISSA project) and highlights SE as *"native environment for circular economy"* (Paladini et al., 2021, p. 1).

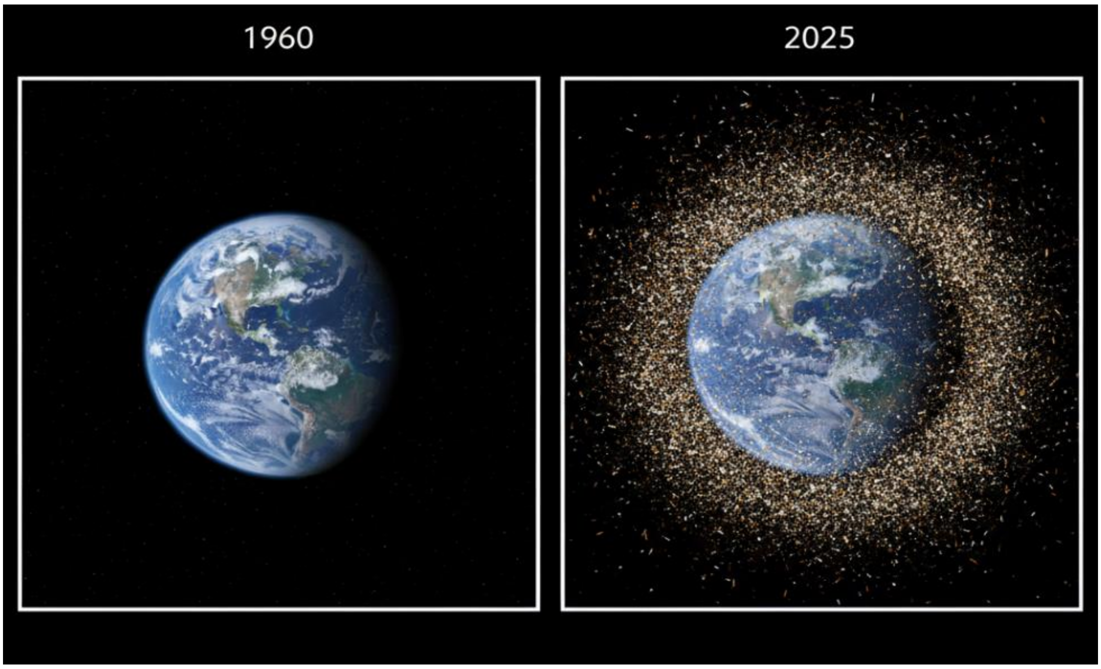

Figure 1. Earth Orbit in 1960 vs. 2025 (AI generated by using source of ESA, 2025/2013)

Despite initial insights and emerging perspectives on the CSE (e.g., Yang et al., 2025), the literature has not yet articulated a structured, comprehensive research agenda capable of guiding a systemic shift from today's largely linear orbital practices toward a viable CSE. This absence of a unifying framework limits cumulative theorizing and can hinder the translation of research into coherent policy and industry roadmaps, at a time when both the economic stakes and the sustainability risks associated with orbital debris are rapidly increasing. This article bridges that gap by developing an integrative framework for the CE–SE intersection and advancing a comprehensive research agenda to support theory building and empirical inquiry on CSE. In doing so, this article positions CSE not as a set of isolated interventions, but as a systemic approach to resource stewardship across space systems and terrestrial ecosystems.

The remainder of this article proceeds as follows. Section 2 details the methodological approach. Section 3 provides the literature review synthesizing the theoretical foundations of the CE and SE. Section 4 presents the key findings articulating a comprehensive ten-point research agenda organized across four strategic pillars. Finally, Section 5 discusses implications and proposes research questions to guide future scholarly inquiry on the CSE.

2. Method

To support the conceptual advancement of this research, this article employs an integrative literature review approach (e.g., Torraco, 2016). This method is particularly suitable for addressing emerging topics, synthesizing fragmented and interdisciplinary bodies of knowledge, and enabling the development of new conceptual linkages and theoretical frameworks (cf. Torraco, 2016, Snyder, 2019). Given the dispersion of research on the CE and SE across fields an integrative approach allowed me to consolidate diverse insights in the emerging research field of CSE. The article follows the three-step approach suggested by Torraco (2016) of (i) planning and identification, (ii) selection and screening, and (iii) analysis and synthesis:

(i) In the initial phase, I performed a scoping review to delineate the thematic boundaries of the study and identify the core research questions and keywords. This phase focused on mapping the intersections between CE and SE. This preliminary literature scan further confirmed the nascent stage of the CE-SE literature.

(ii) In the next phase, a structured search was conducted using Web of Science and Google Scholar, capturing only scholarly work, i.e., peer-reviewed articles, conference proceedings, and theses. The search focused on articles published between 01st of January 2010 and 11th of December 2025, reflecting the most recent evolution of CE and SE scholarship. The following keyword combinations were subsequently used in title (TI) searches: (“Circular Economy” OR “CE” OR “Circular”) AND (“Space” OR “Space Economy” OR “Orbit” OR “Debris”).

Table 1. Literature Search Results

Circular Economy *OR* CE *OR* Circular	**Scholar**	**WoS**
AND	***TI***	***TI***
Space	319	445
Space Economy	3	36
Orbit	146	0
Debris	11	2
Sum	**479**	**483**

As illustrated in Table 1and Figure 2, the search yielded 962 publications. Abstracts were screened for conceptual depth and empirical relevance. Studies were included if they (a) addressed the CE–SE explicitly or/and (b) contributed to understanding CE framings in SE, and vice versa. Following the elimination of duplicates and the systematic application of our inclusion and exclusion criteria, I retained only those sources that offered substantive engagement with both CE and SE (Figure 2).

(iii) I employed a qualitative analysis to examine the selected articles. Following established protocols for interpretive research, I conducted iterative close readings of each article to inductively identify emergent codes grounded in the textual data rather than imposing predetermined theoretical categories. This initial open coding phase generated a comprehensive inventory of concepts related to CE principles and SE practices discussed in the sample. Subsequently, I engaged in a recursive analytical process, moving iteratively between raw codes and higher-order conceptual patterns to identify meaningful relationships and thematic coherence. Through constant comparison and consolidation, I grouped related codes into intermediate categories, which were then subjected to further abstraction and refinement. This hierarchical synthesis ultimately yielded ten thematic domains that captured the multidimensional intersections between SE activities and CE principles. These themes form the conceptual architecture for the research agenda, providing the theoretical foundation for understanding how circularity can be conceptualized within the SE, this is what I conceptualize as the emerging research field of CSE.

Following rigorous full-text screening and qualitative assessment, the final sample comprises 11 articles that explicitly address the intersection of CE and SE. This attrition, from an initial search yield of approximately 1,000 keyword-matched articles, to a final sample of 11 articles reveals a critical theoretical void: while both domains have garnered substantial independent scholarly attention, their conceptual integration remains underdeveloped. This scarcity underscores the urgent need for a structured research agenda capable of catalyzing the CSE as an emerging, yet theoretically underspecified, research field.

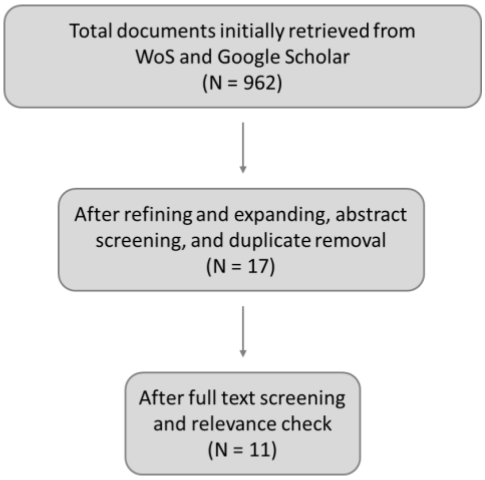

Figure 2. Literature Search flow chart and results

3. Literature Review

3.1. The Circular Economy

The CE has emerged as one of the most influential sustainability paradigms for addressing the intertwined crises of environmental degradation, climate instability, and resource scarcity on Earth (e.g., Geissdoerfer et al., 2017; Schultz & Rhein, 2024). At its core, the CE is predicated on the ambition to decouple economic activity from resource consumption (e.g., Kirchherr, 2022; Schultz & Pies, 2024) by narrowing, slowing, and/or closing resource loops (Bocken et al., 2016). This aspiration has profoundly shaped CE scholarship over the past decade. As a case in point, Kirchherr et al. (2023, p. 7), for instance, conceptualize CE as: *"a regenerative economic system which necessitates a paradigm shift … with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations."*.

Recently, CE scholarship has evolved into a theoretically rich domain organized across three distinct yet interconnected analytical levels, namely macro, meso, and micro (Kirchherr et al., 2017):

At the macro level, CE scholarship investigates systemic and institutional conditions that enable or constrain circularity. This level encompasses critical analyses of e.g., systems thinking approaches (e.g., Valentinov & Schultz, 2025), the complex relationship between CE and economic growth trajectories (e.g., Kirchherr, 2022; Schultz & Pies, 2024;), (supra-)national policy architectures (e.g., Hartley et al., 2020), and emerging scholarship on CE rebound effects that may paradoxically undermine sustainability objectives (e.g., Lowe et al., 2025; Schultz et al., 2024a; Zink & Geyer, 2017).

At the meso level, scholars focus on inter-organizational dynamics and the structural properties of circular ecosystems and supply chains. Key contributions in this domain include i.a. conceptualizations of circular ecosystems (e.g., Geissdoerfer et al., 2025), stakeholder governance in CE to coordinate multi-actor collaboration (e.g., Minoja & Romano, 2024; Schultz et al., 2024b), and investigations of circular supply chains enabling circular material flows (e.g., Farooque et al., 2019; Schultz et al., 2021; Taddei et al., 2022).

At the micro level, research focuses on firm-level strategies, management, and operations. This literature stream has generated substantial insights into circular business model innovation (CBMI), the processes through which organizations redesign value propositions, creation, delivery, and capture mechanisms to align with circular principles (e.g., Geissdoerfer et al., 2020), as well as the development of circular business cases (e.g., Schultz et al., 2025a, b), and the technical and strategic dimensions of circular product design (e.g., Bakker et al., 2018; Bocken et al., 2016).

Collectively, this multi-level architecture provides a comprehensive analytical framework for understanding how circularity can be institutionalized across scales, from individual products to entire socio-economic systems.

3.2. The Space Economy

A prominent publication by OECD (2007, p. 17) defines the SE as "[a]ll public and private actors involved in developing and providing space-enabled products and services. It comprises a long value-added chain, starting with research and development actors and manufacturers of space hardware (e.g. launch vehicles, satellites, ground stations) and ending with the providers of space-enabled products (e.g. navigation equipment, satellite phones) and services (e.g. satellite-based meteorological services or direct-to-home video services) to final users."

The SE has evolved from a government-dominated strategic domain into a dynamic, market-driven ecosystem defined as the aggregate of all economic activities related to the development, production, operation, and commercialization of space-based infrastructure, technologies, and services (Punnala et al., 2025). SE encompasses diverse supply chains, ranging from upstream manufacturing of launch vehicles and satellites to downstream sectors such as Earth observation, telecommunications, and positioning services, which are increasingly integrated into the global digital infrastructure (cf. Tan et al., 2022). As a case in point, Punnala et al. (2025) argue that the sector's current commercial expansion, often characterized as "New Space Economy" is a structural transformation driven by eight critical determinants, including i.a., technological innovation, regulatory frameworks, and geopolitical strategies. Central to this shift is the role of digitalization (e.g., Dias et al., 2022; Bahlmann et al., 2024), where the convergence of artificial intelligence (AI), cloud computing, and big data has significantly lowered entry barriers and operational costs, effectively democratizing access to space data and assets (Yang et al., 2025). With valuations projected to reach enormous economic potentials within the next 20 years, the SE is rapidly transitioning from a niche frontier of national prestige into a fundamental backbone of the modern global economy (cf. Punnala et al., 2025; Elvis & Milligan, 2019).

Recently, advancements in surveillance capabilities have enabled space agencies to establish robust monitoring and modeling frameworks across all major orbital regimes, including Low Earth Orbit (LEO; <2,000 km), Medium Earth Orbit (MEO; 2,000–35,786 km), and Geostationary Earth Orbit (GEO; 35,786 km) (NASA, 2025; Leonard & Williams, 2023). Current assessments by the European Space Agency (ESA) quantify the severe congestion within these zones, identifying approximately 54,000 objects larger than 10 cm, of which only roughly 9,300 represent active payloads. This population is dwarfed by smaller fragments, with estimates exceeding 1.2 million objects between 1 cm and 10 cm, and 140 million particles between 1 mm and 1 cm (ESA, 2025b). As debris density increases in space, so does the risk of collision events. To counteract the projected rise in catastrophic collisions in the next decades resulting from this density (see Figure 3), the ESA develops three key pillars: (i) the implementation of Ecodesign, (ii) the advancement of Zero Debris Technologies, (iii) and the deployment of In-Orbit Servicing (IOS) and Active Debris Removal (ADR) (cf. ESA, 2019).

Taken together, these developments reveal a rapidly commercializing yet increasingly congested SE, making it necessary to take a critical look on the prevalent production and consumption model.

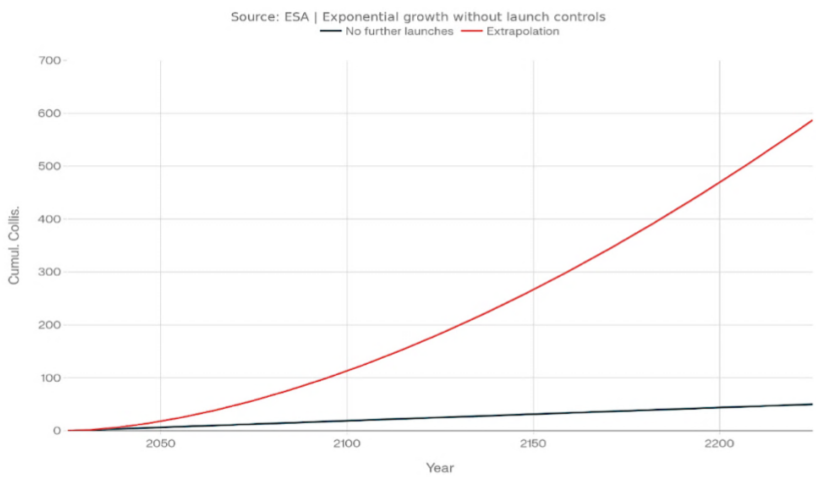

Figure 3. Extrapolation of space debris collisions 2025-2225 (AI, based on ESA, 2024)

3.3. The Circular Space Economy

The CE represents a vital path for addressing ecological pollution issues across various industries, including the aerospace sector (e.g., Dias et al., 2022). The space sector, in particular, is argued to be a *"native environment for circular economy"* due to the inherent constraints on resources, logistics, and mass budgets (Paladini et al., 2021, p.1). The global expansion of the space industry is concurrently driving a critical need for environmentally responsible practices, compelling stakeholders to integrate sustainability thinking and circular practices throughout the space supply chain (e.g., Jones & Jain, 2023; Tan et al., 2022; Bahlmann et al., 2024).

The application of CE principles is bifurcated, addressing both the immediate environmental risks in Earth orbit and the long-term sustainability requirements of deep-space exploration. In Earth orbit, a central concern is the rapidly accumulating population of space debris, which heightens the risk of catastrophic so-called "Kessler Syndrome-style collision events" (Leonard & Williams, 2023, p.19). To further address CE in an orbital context, the so-called "Orbital Circular Economy framework" has been developed to scope and manage CE implementation within the space(-related) industry (Brennan & Vecchi, 2020). Economically, the viability of a CE for space debris is compelling, with analyses of 'reuse' and 'scrap material' scenarios estimating the high-end net value of recovered debris materials could exceed \$1.2 trillion, thus providing a potential commercial justification for material recovery (Leonard & Williams, 2023). However, the commercial feasibility of capturing this value is still questionable. One key enabler of orbital circularity is the role of satellite reuse (e.g., Weiss, 2025) and the future development of IOS, such as refueling, repair, and material harvesting, which are crucial for establishing a closed-loop system in orbit (e.g., Leonard & Williams, 2023). Conversely, for deep-space missions and the establishment of permanent lunar presence, CE-SE models have focused on resource optimization in habitats. While In-Situ Resource Utilization and In-Situ Manufacturing are acknowledged for their importance, the re-purpose of space systems has been identified as an area requiring greater focus (Sanchez, 2022). To guide this, "Design to Re-purpose" has been proposed, which uses metrics like Embodied Energy to quantify waste potential and measure the re-purposability of materials (Sanchez, 2022).

Successful implementation of the CE within the complex space sector relies on several advanced technological and methodological tools. Environmental Life Cycle Assessments (E-LCAs) are vital for quantifying the mission's "cradle-to-grave" environmental impacts across both terrestrial and space domains, effectively identifying opportunities for circularity across the entire system life cycle (Jones & Jain, 2023). Furthermore, the technical feasibility of closed-loop resource management has been historically demonstrated by projects like the ESA-MELISSA program (Micro-Ecological Life Support System Alternative). This program, which focuses i.a. on water treatment and recycling, serves as a comprehensive case study proving the viability of applying complex, closed-loop CE principles in constrained space environments (Paladini et al., 2021). Furthermore, Yang et al. (2025) posit that CE implementation in the space sector requires a multi-level integration of the CE *R-strategies* with relevant data, AI, and systems to enable broader policy and ecosystem redesign. As a case in point, scholarship has demonstrated the potential of hyperspectral imaging as a sustainable and low-cost method for the rapid identification and categorization of mixed space waste materials, which would significantly facilitate effective sorting and recycling operations in orbit or on celestial bodies (Aversano et al., 2024). (A review summary is illustrated in Table 2)

Table 2. Overview of Literature on CE & SE

Authors	Focus/Scope (CE-SE Domain)	Method	Contribution
Paladini et al. (2021)	Foundational CE & Closed-Loop Systems	Case-study approach	Argues the space sector is a "native environment for circular economy"; uses ESA's MELISSA program (Micro-Ecological Life Support System) as a case study to illustrate closed-loop systems in constrained environments.
Brennan & Vecchi (2020)	Orbital Circularity & Frameworks	Resource-based view & Dynamic Capabilities Perspective	Develop the "Orbital Circular Economy Framework" for scoping and managing CE progression within the space industry; investigate principles with evidence from private space actors.
Leonard & Williams (2023)	Orbital Debris & Economic Viability	Calculation method based on authoritative ESA data from "DISCOS" dataset.	Analyze the viability of a CE for space debris; estimates the high-end net value of recovered debris materials could exceed $1.2 trillion, providing a strong economic case for material recovery via In-Orbit Services (IOS).
Sanchez (2022)	Deep Space/Lunar Habitats	Explores the available life cycle analysis (LCA) methods; Design to Re-purpose (DTR) methodology	Propose the Design to Re-purpose (DTR) methodology for lunar surface systems; introduces the use of metrics to quantify waste and measure the re-purposability of space systems.
Weiss (2025)	Orbital Circularity Strategy regarding satellite reuse	Mixed-methods approach	Focuses on the strategic role of satellite reuse as a primary enabler for establishing functional circularity and accelerating the transition toward a CE in space.
Jones & Jain (2023)	Environmental Assessment	Life Cycle Assessments (LCA)	Emphasize the critical role of Environmental Life Cycle Assessments (E-LCAs) for quantifying environmental impacts across terrestrial and space domains, thereby identifying specific CE opportunities.
Aversano et al. (2024)	Recycling Technology & Sorting	Hyperspectral Imaging (HSI) Method	Demonstrate the potential of hyperspectral imaging (HSI) as a sustainable and low-cost technological tool for the rapid identification and categorization of mixed space waste materials to facilitate recycling operations.
Dias et al. (2022)	CE in the Aerospace industry	Theoretical framework	Explore the practices, opportunities, and challenges for applying the CE model specifically within the aerospace industry, linking general CE principles to the broader aerospace sector.
Tan et al. (2022)	Space Value/Supply Chain	Literature review	Provide an examination of sustainability aspects across the entire space value/supply chain through the lens of the CE.
Bahlmann et al. (2024)	Expert Perceptions of CE and SE	Qualitative research approach	Explore expert perceptions on the CE and the space sector, contributing insight into the enablers, barriers, and uncertainties of CSE.
Yang et al. (2025)	Perspective on material efficiency and resources in CSE	Conceptual approach	Posit that CE implementation in the space sector requires a multi-level integration of R-strategies with broader policy and ecosystem redesign.

4. Conceptualizing the Circular Space Economy Research Agenda

While initial scholarly work has established the conceptual fit of CE and SE, this article reveals that the existing body of knowledge is fragmented and fundamentally lacks a structured, multidisciplinary agenda required to guide future research towards a systemic transformation. Based on the literature search and the in-depth literature analysis, I derive and propose the following ten-points Research Agenda (R1-10) for the emerging CSE research field:

4.1. Pillar I (macro level): Orbital Property Rights and Governance

4.1.1. R1: Orbital Property Rights for the 'New' Circular Space Economy The fundamental issue facing the CSE is the existing governance vacuum, creating a so-called "tragedy of the commons", where the absence of clear liability mechanisms incentivizes the over-exploitation of orbital resources and the proliferation of debris (cf. Taylor, 2011; Leonard & Williams, 2023). This failure is illustrated by the lack of punitive consequences for major debris-generating events, such as a 2007 anti-satellite test that created over 3,000 debris objects, demonstrating the inability of current regimes to enforce accountability (cf. Leonard & Williams, 2023). Since international space law remains embedded in a linear, state-centric paradigm ill-suited to the dynamics of the emerging commercial era (e.g., Bahlmann et al., 2024; Paravano et al., 2024), future research must urgently pivot toward conceptualizing the novel legal and economic architectures required to institutionalize circular practices in the 'new' space economy sector.

4.1.2. R2: Orbital Governance for the CSE To effectively advance the CSE, future research must pivot toward restructuring international governance frameworks, such as the *Outer Space Treaty*, to explicitly mandate and incentivize circular practices like end-of-life (EOL) strategies (Yang et al., 2025) and IOS (e.g., Leonard & Williams, 2023). A critical barrier to the commercialization of ADR and material reuse is the pervasive uncertainty regarding laws and legislation for orbital materials and assets; thus, scholars must prioritize the development of legal protocols that define ownership and liability for non-functional assets and in-orbit debris (cf. Leonard & Williams, 2023), creating the institutional legitimacy required for e.g., viable orbital salvage markets. Furthermore, while the *1972 Liability Convention (Convention on International Liability for Damage Caused by Space Objects)* holds launching states accountable for private activities, the private sector itself operates in a regulatory void, reliant largely on soft laws rather than enforceable obligations for post-mission disposal (Yang et al., 2025). To bridge this divide, future governance must move beyond state-centric liability models to establish binding EOL compliance mechanisms for private entities (cf. Yang et al., 2025). Although recent initiatives like the UN's (2021) *"Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space"* and the ESA's (2023) *"Zero Debris Charter"*, i.e., a collaborative effort with industry leaders to eliminate debris generation by 2030, signal a normative shift, converting these commitments into robust, enforceable institutions remains the paramount challenge for the field in the near future.

4.2. Pillar II (meso level): Orbital Circular Ecosystems and Supply Chains

4.2.1. R3: Circular Space Economy Ecosystem The SE is characterized by a remarkable actors' heterogeneity, where national agencies, multinational enterprises, and nascent ventures coexist in a relentless "technological race" defined by experimental learning (Brennan & Vecchi, 2020). Thus, implementing CSE strategies requires addressing a profound institutional transition as the sector shifts from government-led hierarchies to commercially-driven networks (cf. Paladini et al., 2021). Future research must investigate the mechanisms capable of bridging this public-private divide, analyzing how space agencies can evolve from pure operators into "innovation orchestrators" that utilize strategic procurement and data access to anchor private sector development. Specifically, scholars could examine the design of "circular procurement" that may incentivize life-extension and modularity over singular mission focuses, thereby directing private and public investment toward standardized, regenerative infrastructure (cf. Paravano et al., 2024).

The SE offers a unique theoretical vantage point for CE scholarship because circularity has long been an operational imperative rather than merely a strategic choice. As a case in point, Paladini et al., (2021) exemplified this by investigating the MELiSSA project, which, since the 1990s, has operationalized fundamental CE principles well before their widespread adoption in terrestrial industrial contexts. Conceptualized as a scaled-down replication of Earth's ecosystem, MELiSSA integrates e.g., biological photosynthesis and advanced physicochemical processes, such as filtration and bioreactors, to transform metabolic waste into food, oxygen, and potable water. By mimicking the metabolic efficiency of a terrestrial lake to achieve a near-perfect conversion rate without external resupply, MELiSSA demonstrates how extreme resource constraints drive the innovation of closed-loop life support systems. Another example is the shared ISS infrastructure reducing (primary) resource demands in space by e.g., reusing the water (cf. Bahlmann et al., 2024). Consequently, the SE provides a rich empirical setting for investigating how necessity-driven circularity can inform and accelerate the transition of terrestrial industries toward self-sustaining, resilient, and regenerative ecosystems (cf. Paladini et al., 2021). Thus, CSE scholarship should investigate circular ecosystems (cf. Geissdoerfer et al., 2025) in SE contexts that require specific structural properties (e.g., modularity and redundancy) achieved through e.g., intentional network design. In this context, terrestrial initiatives such as industrial symbiosis (e.g., Chertow, 2007) may offer a blueprint for orbital architectures. By explicitly designing for modularity, the CSE can reduce the interdependence strength of critical resource flows, thereby localizing disruptions and mitigating the risk of cascading systemic failures. Consequently, CSE is not just a resource management strategy, but the essential discipline for engineering an industrial metabolism, positioning the CSE as a strategically designed pathway toward resilient, self-sustaining orbital ecosystems.

4.2.2. R4: Circular Space Economy Supply Chain To operationalize circularity within the space sector, research should critically assess the structural dynamics of the existing supply chains, extending beyond traditional linear value creation. The current space supply chains, encompassing upstream, midstream, and downstream activities, can be conceptually clustered into six distinct segments: space manufacturing, launch manufacturing and services, ground infrastructure, space operations, space services and applications, and ancillary services (cf. UK Space Agency, 2022; Tan et al., 2022). Future scholarship should investigate how circular principles of narrowing, slowing, and closing loops can be embedded across these interlinked segments to transform them from isolated value steps into a cohesive, regenerative supply chain network between public and private actors, identifying specific intervention points for each segment.

4.3. Pillar III (micro level): Orbital Circular Business Models, Design, and Technology

4.3.1. R5: Orbital Circular Business Models CE strategies can benefit the development of new business models that can provide sustainable competitive advantage i.a., due to cost savings by e.g., reuse of launching systems and opening up the avenue for new space ventures (e.g., Brennan & Vecchi, 2020; Bahlmann et al., 2024). Research on business model innovation is urgently needed to investigate the specificities of orbital circular business models (OCBMs) (e.g., 'satellite-as-a-service', and in-orbit resource processing) that enable the space industry to realize reuse, remanufacturing, recycling and thus the capture and monetization of the estimated $1.2 trillion value locked in space debris, thereby accelerating the shift to a functional CSE (cf. Leonard & Williams, 2023). For instance, the innovation and implementation of IOS business models (Leonard & Williams, 2023) like satellite reuse (Weiss, 2025) is one crucial lever to address the space debris problem. Research could examine the technological readiness and economic feasibility of scaling up core IOS activities (e.g., refueling, repair, manufacturing) to industrial scale, including the required orbital logistics and manufacturing infrastructure, and the operational challenges of standardized, multi-client service provision. While reusable launch systems, exemplified by SpaceX, have demonstrated how circularity can function as a core cost-saver, potentially reducing launch costs by up to 90% (de Selding, 2016; Brennan & Vecchi, 2020), future research must go beyond these initial cases. Scholars should conduct comprehensive analyses of the long-term cost-benefit dynamics of reusable versus expendable architectures, modeling how such CE-driven shifts reconfigure the broader orbital competitive landscape for business models and lower the barriers to space market entry for firms.

4.3.2. R6: Dynamic Capabilities for CSE Despite the potential of space technology, the transition from public funding to financially viable private applications has historically been inhibited by a deep-seated culture of risk aversion (Brennan & Vecchi, 2020). To overcome this inertia, research must analyze how emerging space actors develop the specific *dynamic capabilities* (i.e., sensing, seizing, and reconfiguring) that are necessary to execute i.a. resource reuse, recovery, remanufacturing, and recycling within orbital business models. Building on the so-called "Orbital Circular Economy Framework" (Brennan & Vecchi, 2020), scholars could investigate how firms like SpaceX, Blue Origin, and Virgin utilize iterative experimentation and action learning cycles to build organizational ambidexterity and absorptive capacity. By framing these iterative development processes as mechanisms for accumulating experiential learning in the face of failure, future research can illuminate how *"circular dynamic capabilities"* enable firms to pursue ambitious sustainability goals while navigating the extreme uncertainties of the commercial space sector.

4.3.3. R7: Circular Design for CSE Systems CSE scholarship could investigate and formalize the integration of CE principles (e.g., modularity, material selection, and Design for Disassembly) ab initio into the design phase of e.g., satellites and space-shuttles, establishing rigorous *"Design for Circularity"* principles in space engineering, operations, and management. Particularly, the design phase plays a critical role in integrating CE principles of narrowing, slowing, and closing the loop into a SE context:

- ***Narrowing:*** Historically driven by the economic imperative of launch costs, narrowing manifests through efficiency-oriented innovation. Private actors like SpaceX and Blue Origin exemplify this by leveraging advanced materials (e.g., carbon fiber composites) and modular architectures (cf. Bahlmann et al., 2024) to minimize structural mass. Furthermore, the integration of collision-avoidance technologies and in-situ additive manufacturing (3D printing) illustrates how technological capabilities can decouple mission value from resource intensity, thereby optimizing the metabolic efficiency of orbital operations (Yang et al., 2025).
- ***Slowing:*** This mechanism focuses on lifecycle extension through recovery and refurbishment. Innovations in soft-landing systems, such as advanced parachutes and airbag cushions, represent a shift from expendable to recoverable asset models. By incorporating impact-resistant designs and precise ground-return capabilities, emerging reusable satellite architectures not only prolong asset utility but also mitigate orbital debris accumulation, fundamentally altering the temporal dynamics of space asset depreciation (Yang et al., 2025).
- ***Closing:*** Representing the most transformative shift, closing strategies involve the reintegration of waste into supply chains. Pioneering ventures such as Orbit Fab and Astroscale are actively prototyping in-orbit services and recycling ecosystems, developing e.g., propellant reclamation, structural disassembly, and debris retrieval. These initiatives signal the emergence of a closed-loop orbital industrial base, where end-of-life assets are reconceptualized not as waste, but as critical feedstock for future missions (Yang et al., 2025).

4.3.4. R8: 'New' Technologies and innovations in CSE Technological innovation represents the primary mechanism through which the SE has transitioned from an exclusive, government-dominated domain to an accessible, market-driven ecosystem capable of supporting circular practices due to increased competition and the race towards 'cost reductions' (e.g., AI systems support SpaceX's Falcon 9 rockets in the landing process enabling reusability). The appearing of disruptive innovations, e.g., satellite miniaturization or reusable launch vehicles, has fundamentally lowered both capital requirements and operational barriers (cf. Bahlmann et al., 2024; Yang et al., 2025), enabling new entrants to challenge traditional aerospace incumbents while simultaneously creating the technical prerequisites for resource circularity in orbit. Among these technological shifts, Bahlmann et al. (2024) and Yang et al. (2025) highlight the integration of AI into space operations as particularly transformative for advancing circular objectives. Exemplarily, AI-driven capabilities, including real-time anomaly detection, predictive maintenance, and autonomous decision support, directly address the operational challenges of extending asset lifecycles and enabling in-orbit servicing, i.e., core mechanisms for slowing and closing resource loops. By continuously analyzing telemetry data to identify incipient failures and optimize performance trajectories, AI systems fundamentally enhance asset resilience and reduce premature disposal. Exemplarily, the ESA OPS-SAT platform provides empirical validation of this potential, serving as an in-orbit testbed where AI applications for on-board analytics, anomaly detection, and adaptive control have been successfully demonstrated under actual space conditions, thus establishing the technical feasibility of embedding AI into circular space infrastructure (cf. Yang et al., 2025).

4.4. Pillar IV (methodologies): Methods and Metrics of CSE

4.4.1. R9: Metrics and Economic Valuation Current estimates of the SE often exclude the benefits of avoided costs. Research should also identify specific new metrics needed to accurately measure the SE's progression from a linear to a circular model, and determine how the economic valuation of positive externalities, such as the impact of satellite applications on achieving specific SDG targets and the value of avoiding a Kessler event, can be integrated into national and global SE accounts (cf. Paravano et al., 2024). Further, the rising probability of a catastrophic Kessler-style collision event (see Figure 3) necessitates new financial and economic approaches and tools. Research could design innovative risk assessment, liability, and insurance models that explicitly account for the avoided costs of preventing a debris cascade and assign liabilities for ADR, thereby creating strong financial incentives for private sector investment in CSE risk mitigation infrastructure. Furthermore, CSE may require a metric that can also quantify the CE-SE symbiosis (cf. Paravano et al., 2024), i.e., the space sector's positive impact on terrestrial circularity. Research could investigate and define a specific set of metrics (e.g., "Circularity Space Index") to quantify resource savings and waste reduction achieved in orbital environments and further by satellite applications (e.g., optimization of logistics, precision agriculture, and resource monitoring) on earth.

4.4.2. R10: Life Cycle Assessments for the Circular Space Economy The complexity of space missions demands a holistic assessment methodology, e.g., *Life Cycle Assessments* (Jones & Jain, 2023). Research must focus on the development and standardization of Life Cycle Assessments tailored for the space industry, moving beyond siloed analyses on terrestrial environments. This work could advance LCA methods (e.g., Sanchez, 2022) to quantify the net environmental impact of circular space activities (e.g., satellite life extension vs. replacement, debris removal vs. collision risk) and systematically identify the most impactful CE strategies across the entire lifecycle on earth and in space.

Table 3. Summary of the Research Agenda for CSE

Pillar	Research Agenda	Research Questions
I: Macro-Level (Orbital Property Rights and Governance)	R1: Orbital Property Rights	What legal mechanisms can establish enforceable property rights for e.g., defunct satellites and space debris on global scale? What economic and legal models can incentivize debris ownership?
	R2: Orbital Governance	What enforceable governance mechanisms can hold private entities accountable for post-mission debris mitigation beyond state-centric liability models? How can voluntary initiatives (e.g., ESA Zero Debris Charter) be transformed into binding international standards?
II: Meso-Level (Orbital Circular Ecosystems and supply chains)	R3: CSE Ecosystems	What procurement contract designs can effectively incentivize modularity and life-extension over mission-specific optimization? How can space agencies transition from operators to "innovation orchestrators" that strategically anchor private CE developments?
	R4: CSE Supply Chains	Where are the critical intervention points across the six space supply chain segments (manufacturing, launch, ground, operations, services, ancillary) for embedding What collaboration types can transform linear supply chain segments into an integrated, regenerative network?

Table 3 (cont.). Summary of the Research Agenda for CSE

Pillar	Research Agenda	Research Questions
III: Micro-Level (Orbital Circular Business Models, Product Design, and Technology)	R5: Orbital Circular Business Models	What business model innovations elevate e.g., satellite-as-a-service and in-orbit resource processing economically at scale?
		How do reusable launch systems (e.g., SpaceX) reconfigure competitive dynamics and entry barriers in the space market?
		What type of business model innovations are suitable for capturing and monetizing the trillion $-Dollar values in orbital debris?
	R6: Dynamic Capabilities for CSE Innovation	What specific sensing, seizing, and reconfiguring capabilities (i.e., dynamic capabilities) enable firms to successfully transition from expendable to reusable space architectures?
		How do iterative experimentation and learning cycles build organizational ambidexterity for managing circular and linear business models simultaneously?
	R7: Design for Circularity in CSE	What specific design principles (modularity, standardized interfaces, material selection) can enable narrowing, slowing, and closing strategies?
		How can Design for Circularity be integrated ab initio into satellite, rocket, launch system engineering to facilitate in-orbit servicing and component recovery?
		What is needed to foster interoperability and circular compatibility across multi-vendor space systems?
	R8: 'New' Technologies	How do new technologies (e.g., AI) affect the opportunities and economic feasibility of enabling and scaling narrowing, slowing, and closing strategies in CSE?
IV: Methodologies (Methods and Metrics)	R9: Economic Valuation and Avoided Costs	How can the avoided costs of catastrophic Kessler events be quantified and integrated into SE accounts?
		How should the positive externalities of CE strategies be economically valued and attributed to CSE in practice?
		What methodologies can distinguish between circularity achieved in-orbit versus circularity enabled on Earth through space-based services?
	R10: Life Cycle Assessments for CSE	How should Life Cycle Assessment (LCA) methodologies be advanced to account for the unique environmental conditions and timeframes of orbital operations?

5. Discussion and concluding remarks

The foundational literature on the SE and CE has established the conceptual groundwork for the CSE, noting the unique physical constraints of the orbital environment that align with e.g., closed-loop systems (Paladini et al., 2021). Furthermore, the substantial economic viability is empirically supported, with estimates placing the value of recoverable orbital assets up to \$1.2 trillion (Leonard & Williams, 2023). However, the \$1.2 trillion estimate proposed is predicated on in-orbit servicing, reuse, and material processing rather than terrestrial return and thus presents a critical economic barrier to the realization. The review reveals that the existing scholarship, while critical, remains fragmented, addressing individual cases, such as the MELISSA project (e.g., Paladini et al., 2021) or the necessity of satellite reuse (e.g., Weiss, 2025), in isolation. Thus, this initial body of work suffers from a severe gap: the absence of an integrated, multidisciplinary agenda capable of guiding the complex transition from linear SE practice to a self-sustaining, orbital circularity.

The conceptualization of CSE and the research agenda articulated herein (e.g., Table 3) are the scholarly response to this deficiency. The four strategic pillars are not merely descriptive categories; they are delineated as the interdependent prerequisites for CSE realization. For the academic community, this agenda serves as a vital call for structured investigation into the causal interdependencies that currently impede circularity. For instance, the property rights and governance pillar (Pillar I) compels legal and financial scholars to move beyond acknowledging the absence of property rights (Leonard & Williams, 2023) to developing actionable regulatory frameworks that explicitly define ownership of defunct assets and introduce new liability models. The outcome of this legal research directly informs the CE ecosystem and supply chain pillar (Pillar II), where scholars are challenged to investigate circular ecosystems and supply chains in the context of SE. Recovery is not a single technology but a multi-actor production system, so research should specify how actors can use e.g., procurement and data-access to create demand certainty for in-orbit servicing and reuse, while designing circular ecosystem architectures (e.g., modularity and redundancy) that prevent single-point failures and allow recovered components to re-enter standardized orbital supply chains.

Moreover, the agenda challenges engineering and design disciplines to move from feasibility studies to industrial standardization. The Orbital Circular Business Model (OCBM) and Design & Technology pillar (Pillar III) requires rigorous research into scaling In-Orbit Services and formalizing "Design for Orbital Circularity" standards ab initio. This includes investigating the technological readiness levels and market dynamics required for scaling orbital manufacturing and services. Finally, the Methods pillar (Pillar IV) urges quantitative scholars to develop advanced, space-specific measurement instruments, such as e.g., 'Circularity Space Index,' to ensure accountability. This metric development must move past general LCAs (cf. Jones & Jain, 2023) to accurately quantify the positive (and negative) externalities of the CSE, also including calculated values of averted catastrophic debris events. By addressing these interdependent challenges across the four pillars, future research can directly furnish the empirical evidence and conceptual tools required by industry and policymakers to develop a functional CSE.

This study offers three core theoretical contributions to the emerging CSE literature. First, it provided the conceptual integration of SE and CE by theorizing CSE as a multi-level phenomenon, linking macro-level property-rights and governance with meso-level ecosystem/supply-chains and micro-level business model, design choices, and technological innovations. Second, it contributes first insights into mechanisms through which circular strategies (e.g., narrowing, slowing, closing) translate into orbital impacts, positioning in-orbit services and reuse as pivotal link between resource value and circularity, rather than assuming terrestrial return as the dominant circular route (cf. Leonard & Williams, 2023). Third, it contributes a (future) research-organizing framework by articulating a ten-point agenda that specifies where future theory-building is most needed, thus providing a coherent platform for cumulative knowledge development in a currently fragmented domain. Although the article's contributions are unique to the emerging CSE research field, several limitations should be acknowledged. The article is constrained by the scope and maturity of the underlying SE-CE literature, limiting the ability to draw robust generalizations across e.g., mission types, actor categories, etc. Finally, the study cannot empirically validate the derived insights from literature proposed in the four pillars (and ten points), highlighting the need for future conceptual and empirical work that validates boundary conditions and moderating factors across different governance systems and market contexts.

In conclusion, while existing research successfully lays the groundwork for the CE-SE intersection, future research is urgently required to provide the essential empirical and conceptual foundation for policymakers and industry leaders to realize the CSE. The proposed research agenda provides a roadmap to translate initial insights into systemic, commercially viable, and ecologically essential solutions in the 2030s, ensuring that CSE becomes an enabling model for sustainable development on Earth and in Space.

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