engineering proceedings

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Proceeding Paper

A Systematic Review of Circularity and Sustainability Strategies in the Space Industry †

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† Presented at the 15th EASN International Conference, Madrid, Spain, 14–17 October 2025.

Abstract

This study presents a systematic analysis of circular economy (CE) and sustainability strategies in the space industry. Based on a comprehensive literature review across Scopus, IEEE Xplore and Web of Science, it identifies current and future needs as well as digital technology and organizational demands for implementing circularity in space systems. Findings reveal that established CE strategies are scarcely applied to space missions, while digitalization efforts mainly focus on system optimization. Furthermore, the most relevant CE strategies for the space industry were determined. Future research should explore the transfer of proven CE approaches from terrestrial industries beyond the Kármán line and assess the potential of orbital resource loops.

Keywords: circularity; sustainability; circular economy strategy; space systems; digitalization; lifecycle thinking

1. Introduction

The increasing societal and economic relevance of the space industry is accompanied by a growing responsibility to address its environmental impacts [1,2]. While space-based technologies play a pivotal role in monitoring climate change and supporting sustainability on Earth, the sector itself contributes to environmental degradation through intensive material and energy consumption, launch emissions, space debris and limited End-of-Life (EoL) strategies [3]. On Earth, circular economy (CE) strategies—such as the 9R framework from Potting et al. [4] with the nine strategies including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover—are already embedded across industry sectors such as the automotive industry [5] and electronics [6]. These strategies enable resource efficiency, waste minimization and lifecycle optimization. Yet, transferring CE principles to space introduces unique constraints, including harsh environmental conditions, limited accessibility, uncertain cost structures and the absence of established sustainability assessment methods. Recent initiatives by the European Space Agency (ESA) have begun exploring circularity visions for space, advocating for in-orbit servicing, manufacturing and recycling [7,8]. These visions suggest a transition toward a closed-loop space ecosystem that preserves resources and ensures long-term orbital sustainability. Nevertheless, scientific foundations, technological enablers and lifecycle approaches remain underdeveloped [3]. The aim of this paper is to identify current and future needs for sustainability and circularity strategies across the space sector. To achieve this, a literature review of scientific publications, industry white papers and selected gray literature was conducted. The review focuses on two research questions:

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Academic Editors: Spiros Pantelakis, Andreas Strohmayer and Gustavo Alonso

Published: 19 April 2026

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- RQ1: What are the current and future needs for sustainability and circularity strategies across the space sector?
- RQ2: What are the technological and organizational requirements for embedding circular economy in space systems?

2. State of the Art

2.1. Circular Economy on Earth

Circularity implementation on Earth typically spans over all lifecycle phases: research and development, design, engineering, manufacturing planning, supply chain management, manufacturing, use, service, maintenance and EoL [9]. Mature CE frameworks provide validated solutions, including design-for-disassembly, remanufacturing infrastructures, Digital Product Passports (DPP) and material tracking systems (cp. [10,11]). Many terrestrial sectors rely on digitalization to enable CE, e.g.:

- Digital twins facilitate predictive maintenance [12].
- Interoperable data models ensure value-chain transparency [13].
- Lifecycle sustainability assessments evaluate environmental impacts [14].

Digitalization is a central enabler for CE in complex systems [15]. In the automotive industry, digitalization is established as a foundation for circularity; e.g., DPPs [16] and interoperable data spaces [17] support transparent supply chains and closed-loop cycles.

2.2. Circularity Beyond the Kármán Line

Circularity beyond the Kármán line [18] faces unique technical and systemic constraints that distinguish the space sector from terrestrial applications. Space systems operate under extreme conditions, e.g., marked by radiation, vacuum, thermal cycling and micrometeoroid exposure. These factors make conventional CE strategies difficult to implement. Additionally, in-orbit operations limit opportunities for physical intervention. As a result, the prevailing lifecycle model remains linear, characterized by "launch–use–decommission" [19]. Existing sustainability assessments, largely based on Earth-bound Life Cycle Assessments (LCA) methodologies, cannot adequately model orbital externalities such as debris proliferation, long-term collision risks or the environmental impact of derelict objects [20,21].

Current digital practices focus on mission performance, simulation and system verification, while lifecycle-wide data continuity is largely absent [22]. Data architectures are fragmented and proprietary, preventing interoperable models. Moreover, satellites provide only coarse health-monitoring data with a limited reliable assessment of component conditions. Digital tools for environmental assessment in orbit are limited in, e.g., modelling orbital debris risks or long-term environmental effects [19].

3. Methodology

The study follows a systematic literature review (SLR) approach to examine the current state of CE in the space sector and to identify needs and requirements. The review is structured according to the PRISMA methodology [23]. Three scientific databases (Scopus, Web of Science and IEEE Xplore), with high relevance for engineering, sustainability and space research, were selected to provide comprehensive coverage of scientific publications. A combined Boolean search string "("space industry*" OR "*satellite*" OR "space system*" OR "space material*" OR "space mission*") AND ("circular economy" OR "circularity")" was used.

https://doi.org/10.3390/engproc2026133016

3.1. Screening and Selection Procedure

After the initial database search duplicates were identified and removed. The remaining records were then subjected to a multi-stage screening process. The first stage involved a title- and abstract-based relevance check to eliminate publications that did not address circularity- or space-related technological systems. The final stage consisted of a full-text review aimed at identifying publications that provided substantive insights into circularity strategies specifically within the space domain.

3.2. Literature Analysis

The full-text review focused on the lifecycle phases and the specific CE strategies which are proposed or analyzed in the publications. Studies were also assessed with respect to their impact on environmental sustainability. The analysis was conducted iteratively: insights from individual publications were grouped into thematic clusters, which were then aligned with the two central research questions. The synthesis builds the basis for assessing the state of CE in the space sector and for formulating implications for future research and industry practice.

4. Results

The SLR returned a total of 271 publications. After the screening procedure was conducted, 13 papers were included for the detailed analysis; see Figure 1. The SLR reveals a research landscape that is still emerging at the intersection of CE and space systems. Although the number of publications directly addressing circularity in the space sector remains limited, the analyzed studies provide valuable insights into current priorities, technological developments and existing gaps. In the following sections, the results are presented along the two research questions.

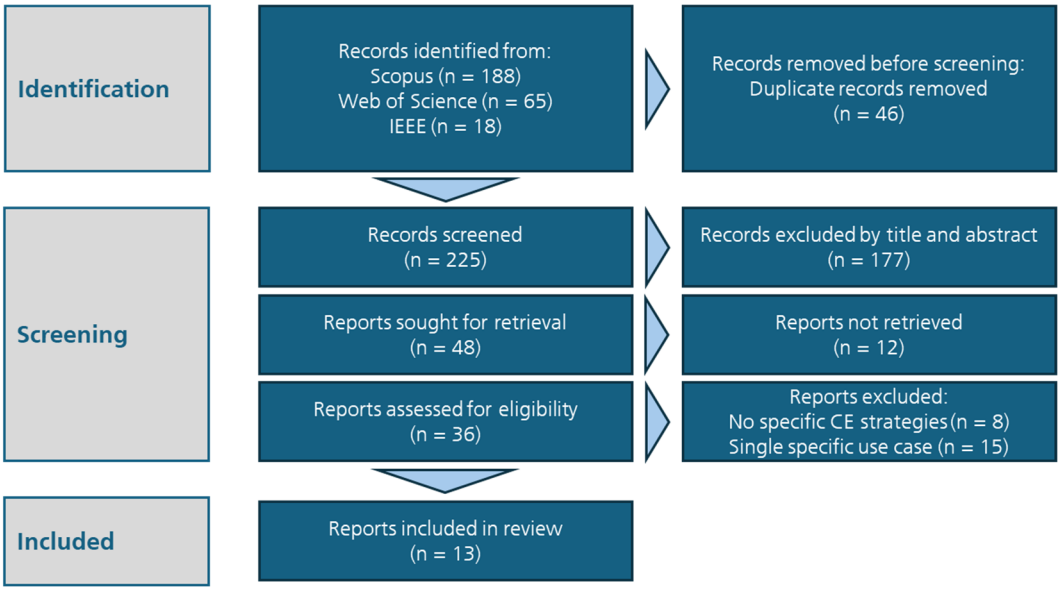


Figure 1. Results of the SLR with the number of identified publications.

4.1. RQ1: Current and Future Needs for Sustainability and Circularity Strategies

Contemporary needs examine adopting lifecycle thinking across all mission phases: design, manufacture, launch, operation and EoL. Cradle-to-grave LCA is recommended to quantify trade-offs (e.g., launch emissions, material choices) and to prioritize eco-design interventions. Agencies and operators must embed LCA and screening tools into mission planning to identify lowest-impact alternatives. The major findings are:

- An immediate need is to prevent and actively manage orbital debris by combining design for deorbit ability, end-of-life capture/removal and on-orbit servicing to extend asset lifetimes. Minimizing debris generation reduces both safety risk and the long-term material losses that undermine circularity [24].
- For long-duration human exploration, closed-loop life-support and bioregenerative systems are essential. Robust water recovery, waste valorization, in situ food production (hydroponics/aeroponics/fogponics) and oxygen/CO_2 management will reduce resupply dependency and enable genuine loop closure for consumables. Demonstrations and scale-up of BLSS subsystems are therefore high priorities [25].
- Material-level circularity requires reliable identification, separation and processing of mixed waste streams (metals, polymers, composites, textiles, batteries). This demands non-destructive material sensing in low gravity and compact recycling/manufacturing systems (e.g., in-space extrusion, catalytic depolymerization) to convert waste into usable feedstock. Quantitative circularity metrics must also be developed for spacecraft and ground assets [26].

Finally, policy, governance and market mechanisms must evolve. Harmonized standards for sustainability reporting, procurement criteria that reward circular design and collaborative frameworks (industry–agency–academia) are necessary to translate technical potentials into operational practice [27,28].

4.2. RQ2: Technological and Organizational Requirements to Embed Circular Economy in Space Systems

Technologically, three linked clusters emerge (closed-loop, materials and hardware of space systems). The major findings are:

- Closed-loop life-support and resource processing: Mature water- and air-reclamation modules, biological reactors for nutrient and carbon recycling, compact photobioreactors for algae and robust plant-growth systems adapted to microgravity (with fogponics and aeroponics promising higher efficiency) are foundational for crewed habitats and to reduce material throughput from Earth. Technology readiness must be advanced through terrestrial analogue testing and microgravity demonstrations [29].
- Materials sensing, separation and conversion: Reliable, rapid material identification (e.g., hyperspectral imaging and machine-learning classifiers) enables sorting and routing to appropriate recycling pathways; electrochemical, photo-/electrocatalytic and enzymatic processes appear promising for safe, low-temperature depolymerization and metal recovery suitable for space constraints. In-space additive manufacturing is integrated with recycling and closes loops for parts and spares [30].
- Compact, modular reactor and processing hardware: Space applications demand high atom-economy, low mass/volume, and low-energy reactors (flow reactors, compartmentalized catalyst arrays) that can operate with limited maintenance. Catalytic approaches (heterogeneous, biocatalysis, plasma catalysis) offer routes for fertilizer synthesis, ammonia/nitrogen fixation and organic waste valorization in habitats and resource-scarce sites. Demonstrating integrated catalytic flows will be critical [31].

Organizational requirements are interlinked and interdependent with the technology requirements. They cannot be considered completely in isolation from one another, but can nevertheless be grouped in three clusters as follows:

- Institutionalizing lifecycle and circularity metrics within procurement, design reviews and mission approval processes is necessary to ensure early incorporation of sustainability goals. LCA pilots and standardized methods will provide the evidence base for policy changes [32].

- Cross-disciplinary governance and partnerships. Embedding circularity requires collaboration across engineering, chemistry, life-sciences, operations and policy groups; public–private consortia and shared testbeds (ground and LEO) accelerate technology maturation and consensus on standards [33].
- Data transparency and open reporting. Quantitative circularity indicators, public data on material flows, recycling yields and environmental impacts will reduce uncertainty and mobilize investment. Currently, few papers report quantitative circularity; improving data availability is an organizational priority [34].

4.3. Synthesis

The literature indicates a clear pathway: adopt lifecycle thinking and LCA-informed eco-design now (ground and space assets); prioritize development and demonstration of BLSS, compact recycling hardware and sensing/classification capabilities; create governance, procurement and partnership mechanisms that reward circular outcomes. Technological maturation must be accompanied by systematic data collection and standardization so that circular practices become measurable, reproducible and economically viable. Together, these steps will enable the transition from isolated linear thinking to mission-level circularity that preserves orbital and planetary environments while increasing mission resilience [27,28,35,36].

5. Conclusions and Outlook

The systematic review highlights that the integration of CE principles into the space sector is still in its formative stage, with substantial technological and organizational gaps. Yet, it also reveals considerable potential for transforming current linear mission models into more sustainable and regenerative models. Building on the findings, several future research directions emerge that are essential for advancing the field; cp. Figure 2 and the following topics.

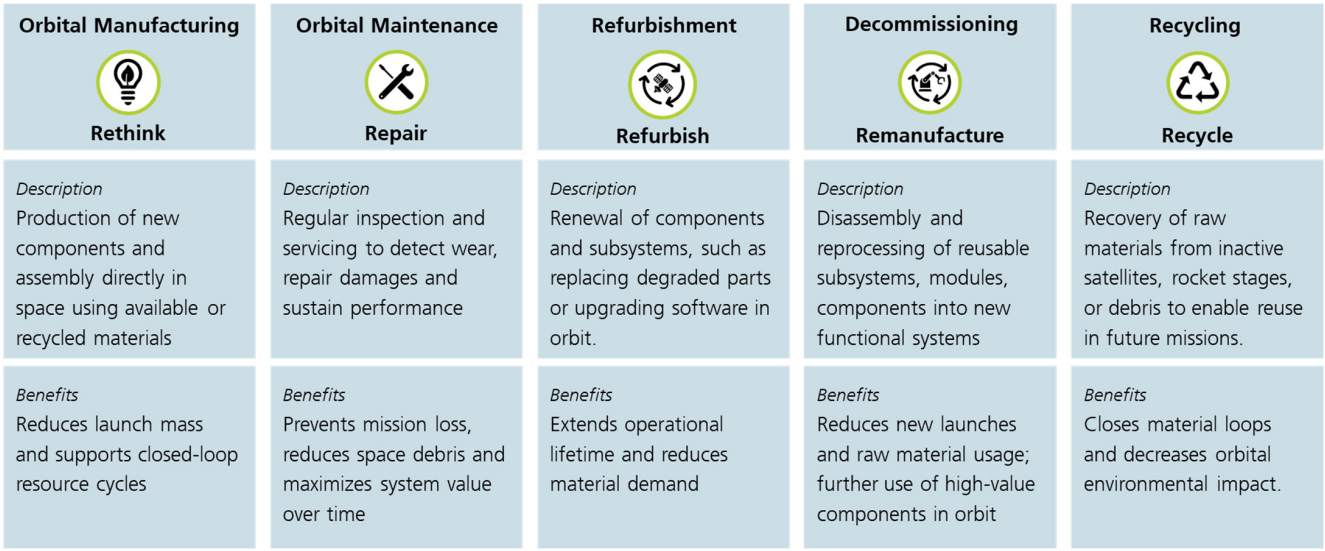


Figure 2. Potentials of the circular economy in orbit.

5.1. Identifying Feasible CE Strategies for Space Contexts

While terrestrial industries provide a rich repository of CE methods, not all strategies are directly applicable beyond Earth's atmosphere. Future research must therefore focus on systematically identifying which circularity approaches—including reuse of subsystems, life extension or material recovery—can be realistically implemented in orbital environ-

ments. This requires a deeper understanding of the constraints posed by microgravity, radiation, thermal cycling and limited accessibility. Novel space missions can be circular; e.g., in-orbit intervention without compromising mission reliability is enabled.

5.2. Lifecycle Integration and Systems-Level Approaches

Developing a comprehensive CE framework for the space sector requires integrating circularity across all lifecycle phases, from mission conception to EoL. Current practices remain dominated by mission-centric engineering, but circularity demands an ecosystem perspective. Future research should therefore explore lifecycle-spanning models. Such models must also account for the dynamics of satellite constellations and the cumulative effects of successive mission generations.

5.3. Orbital Sustainability Metrics and Environmental Assessment

A critical research need concerns the development of environmental assessment methods suitable for orbital systems. New indicators are required to quantify debris generation potential, collision risks, orbital capacity and long-term environmental impacts. Integrating these parameters into LCA tools will enable decision-makers to compare alternative mission designs and circularity strategies. This domain also intersects policy, e.g., standardized sustainability metrics and regulatory frameworks.

5.4. Digital Product Passports and Interoperable Data Spaces

Digital product passports (DPPs) have the potential to transform transparency and traceability in the space sector, enabling better-informed decisions during design, operation and EoL. Research is needed to develop standardized data models, governance structures and interoperability mechanisms that allow mission stakeholders to share relevant lifecycle data without compromising security. Complementary work on digital twins, real-time condition monitoring and autonomous diagnostics will further strengthen the digital foundation required for circularity in orbit.

5.5. Socio-Technical Infrastructures for a Closed-Loop Space Economy

Finally, the transition toward a circular space economy will require new socio-technical infrastructures. This includes business models for in-orbit services, international coordination mechanisms, shared robotic platforms, and regulatory innovations. Future research should explore how these elements can co-evolve scalable circularity solutions. Understanding the interplay between technical feasibility, economic incentives and policy frameworks will be essential for building a regenerative space ecosystem.

Author Contributions: Conceptualization, J.S. and K.L.; methodology, J.S.; formal analysis, J.S.; writing—original draft preparation, J.S. and S.W.; writing—review and editing, T.R. and K.L.; visualization, J.S.; supervision, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data was created in this research.

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

Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular Economy
DPP	Digital Product Passport
EoL	End-of-Life
LCA	Life Cycle Assessment
RQ	Research Question
SLR	Systematic Literature Review

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