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REVIEW

A Systematic Review of the Space Industry's Environmental Burden within Earth System Limits

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ABSTRACT

The environmental impacts of the modern space industry have expanded rapidly with the rise of commercial launch services, satellite mega constellations, and reusable spacecraft. Despite growing global interest, these impacts remain poorly understood and largely unregulated. This paper systematically reviews the environmental footprint of contemporary space activities, synthesizing evidence across five domains: rocket emissions, orbital debris, atmospheric reentry, light pollution, and material resource use. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, over 80 peer-reviewed studies and international agency reports were analyzed. Findings reveal significant, yet underregulated, impacts on atmospheric chemistry, orbital sustainability, and terrestrial resources. While mitigation efforts, such as green propellants, debris removal technologies, and sustainability rating systems, are emerging, their adoption remains fragmented and largely voluntary. The review identifies persistent research and policy gaps, including the lack of transparent life cycle assessments and robust global standards. It further highlights the accelerating pace of space commercialization and the increasing involvement of private actors, which intensify governance challenges and complicate accountability mechanisms across jurisdictions. Additionally, disparities in technological capacity between nations raise concerns about unequal environmental burdens and access to orbital resources. It calls for the integration of space activities into comprehensive environmental governance frameworks

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and the advancement of interdisciplinary, systemic solutions to ensure the long-term sustainability of both orbital and terrestrial environments.

Keywords: Space Industry; Satellite Constellations; Rocket Emissions; Space Debris; Orbital Pollution; Environmental Impact; Atmospheric Chemistry

1. Introduction

The rapid expansion of the modern space industry marks one of the most significant technological evolutions of the 21st century. No longer dominated solely by government-backed missions, the sector now includes a diverse range of private actors and commercial interests. This surge in launches and orbital infrastructure has enabled new services, such as satellite internet, Earth observation, and climate monitoring, but has also introduced a largely unexamined burden on Earth's environmental systems [1].

Despite the space industry's reputation for innovation and frontier-pushing ambition, its environmental impacts remain under-assessed and poorly regulated. While in the past environmental reviews have been concentrated in terrestrial industries, such as energy, travel and agriculture, activity in the orbital and upper atmosphere have historically sat on the interstices of the environmental conversation [2,3]. However, changes in the space environment, such as a rapid increase in the number of launches, a public shift towards new reusable rocket classes, and the go-ahead of mega-constellations involving tens of thousands of satellites, suggest that the environmental impact of space activities can no longer be considered negligible. Instead, it is a growing area of anthropogenic influence, which cuts across the fields of atmospheric chemistry, space debris dynamics, light pollution and global materials flows [4].

One of the most immediate concerns is the effect of rocket launches on the atmosphere. Launch vehicles emit a complex mix of greenhouse gases, particulate matter, and ozone-depleting substances directly into the upper atmosphere, a region where chemical interactions are particularly sensitive and poorly buffered. Solid rocket propellants (for example, in some booster stages) give off chlorine compounds which deplete the ozone in the Earth's stratosphere [5]. Paradoxically, black carbon particles emitted from kerosene and methane-burning rockets can also deposit in the stratosphere and absorb solar radiation, thus disturbing local ganglia of radiative exchange. These emissions are of novel composition as well as altitude, unlike those in surface transport and aviation and are, for the most part, not included in national and international emissions inventories [6–8].

Another growing issue is the accumulation of space debris, where emergence of giant satellite mega constellations (systems with thousands of interconnected satellites operating in Low Earth Orbit (LEO)) substantially amplifies the risk of collisions and fragmentation. These debris can cause a domino effect, Kessler Syndrome, where multiple collisions result in additional debris and heighten the risk of another collision. These environmental impacts go beyond space where fragments from reentering satellites can deposit aluminum and other metals into the upper atmosphere, while the light pollution from densely packed orbital constellations impairs astronomical research and disrupts nocturnal ecosystems on Earth [7,9].

In addition to launch emissions and orbital congestion, the space industry imposes terrestrial impacts across its life cycle. Rare earth elements/metals and composite materials necessary for spacecraft and propulsion system construction have tremendous environmental footprints—habitat destruction, water contamination, and energy-intensive manufacturing. These effects are exacerbated by the absence of formal Life Cycle Assessments (LCAs) in the aerospace domain that traditionally has favored performance and mission success over sustainability aspects.

Despite these diverse impacts, the environmental impact of the contemporary space industry is somewhat fragmented within academic research. Existing studies mainly concentrate on a fragmentary (for example rocket emissions or space debris) and less on holistic environmental assessments [10–12]. Moreover, space activities are also not particularly congruent with current sustainability frameworks, like the planetary boundaries concept or the Paris Agreement goals. Planetary boundaries refer to scientifically defined thresholds that delineate a safe operating space for humanity within Earth system processes, beyond which irreversible environmental change may occur.

The lack of environmental regulation in space and the increasing speed of commercial development create a policy gap, where significant unintended effects on both Earth systems and space assets could result. This paper fills this important gap by offering the first systematic review of the environmental impacts of modern space industry. It considers the life cycle of space activities across a range of potential impacts, from resource extraction and launch emissions through to orbital debris and reentry effects with a view to identifying key impact pathways, knowledge gaps, and regulatory challenges. The review intends to contribute to a broader understanding of how space activities intersect with planetary sustainability, and to propose directions for future research, governance, and environmental accountability [13].

The structure of this paper is as follows: Section 2 outlines the methodology used for the systematic review, including database selection and screening criteria. Section 3 presents the historical and technological context of the space industry's growth. Section 4 presents pathways for reducing the environmental footprint of the space industry, followed by Section 5 that details the specific knowledge gaps and research needs, followed by a conclusion, reflecting on the urgency of integrating space into environmental frameworks as humanity's extraterrestrial ambitions continue to expand.

2. Methodology

This review systematically synthesizes the current literature on the environmental footprint of the modern space industry, following the PRISMA framework to ensure transparency and reproducibility [14]. Peer-reviewed studies, technical assessments, and select grey literature were included to capture a comprehensive view of impacts from rocket launches, satellite operations, reentry phenomena, and space debris proliferation. The review addressed three guiding questions: (1) What are the major environmental impacts of space activities? (2) How have these impacts been characterized and measured? (3) What key knowledge gaps and regulatory needs remain?

A targeted search was conducted across Scopus, Web of Science, Google Scholar, NASA ADS, and IEEE Xplore, using combinations of relevant keywords and Boolean operators. Searches were limited to English-language publications from 2000 to 2025, with foundational older works included as needed. After screening 1,400 articles and removing duplicates and irrelevant studies, 80 publications were retained for final analysis.

A qualitative thematic synthesis was conducted, organizing findings into five core domains: launch emissions, orbital debris, atmospheric reentry, light pollution, and material/resource use. Cross-cutting themes such as planetary boundaries and environmental governance were also examined. Limitations include restricted access to proprietary data from private aerospace firms, a focus on environmental (rather than social or technical) impacts, and the rapidly evolving nature of the field. Despite this, the review offers a structured and up-to-date synthesis for researchers and policymakers.

Quantitative estimates reported in the reviewed literature are subject to substantial uncertainty arising from limited observational data, proprietary industry information, model assumptions, and rapidly changing launch and deployment rates. Reported values (e.g., emissions, reentry mass fluxes) should therefore be interpreted as indicative orders of magnitude rather than precise measurements. Addressing these uncertainties requires coordinated measurement campaigns, standardized reporting, and transparent data sharing.

3. Literature Review

3.1. Historical Trajectory and Environmental Relevance

Over the past two decades, the space industry has shifted from state-driven missions to a rapidly expanding commercial sector. This transformation has brought new actors, technologies, and ambitions, resulting in a broader range of environmental pressures that remain insufficiently addressed in global sustainability frameworks. Understanding this evolution is crucial for assessing the environmental footprint and urgency of the impacts discussed in this review. Historically, space activities were dominated by national governments, with missions driven primarily by geopolitical competition. Early launches, such as Sputnik 1 and the Apollo program, were infrequent and largely symbolic. Environmental impacts during this era were minimal, not because they did not exist, but due to the limited number of launches, typically fewer than 60 per year, mostly for defense or scientific purposes [15].

The early 21st century marked a major shift in the space sector, as privatization, deregulation, and technological innovation drove rapid commercialization. The introduction of reusable rocket technology dramatically reduced launch costs, enabling a wider range of actors, including private companies, universities, and developing nations, to access space. This democratization of access has accelerated launch frequency and intensified the associated environmental pressures [16].

The rise of satellite mega constellations is the most prominent outcome of this commercial expansion. Unlike traditional large satellites launched individually, mega constellations involve thousands of small satellites deployed in coordinated groups. This shift has dramatically increased launch frequency, orbital density, and the number of reentry events, intensifying environmental pressures on both the orbital environment and the atmosphere. This rapid increase in launch frequency has significant environmental consequences. Most launches employ multi-stage rockets that release emissions directly into the stratosphere and mesosphere, affecting ozone chemistry and radiative balance in ways distinct from terrestrial transport. The scale and altitude of these emissions present unique challenges for atmospheric science and environmental regulation [17,18].

Orbital saturation has reached a critical threshold, with the number of active satellites increasing more than fourfold in less than a decade [19]. This growth heightens the risk of collisions and generates persistent space debris, some of which can remain in orbit for centuries. Fragmentation events, whether accidental or intentional, have produced tens of thousands of trackable objects and hundreds of millions of smaller particles. The resulting risk of a cascade failure, known as Kessler Syndrome, now threatens both satellite infrastructure and the long-term sustainability of near-Earth space [20].

Increasingly frequent and unpredictable satellite reentry events present new environmental challenges. While many small satellites are designed to burn up during reentry, recent studies show that some materials, especially aluminum-rich components, survive and deposit metals in the upper atmosphere. These deposits may influence stratospheric cloud formation and atmospheric chemistry, but the rates and trajectories of reentry events are variable, making environmental modeling complex and uncertain [21].

In addition to emissions and debris, the terrestrial impacts of the space industry are substantial. Manufacturing rockets, satellites, and ground infrastructure requires significant material and energy inputs, often relying on rare earth elements, advanced alloys, and composites. Extraction of materials such as lithium, cobalt, and rare earths frequently occurs in regions with limited environmental oversight, leading to habitat loss, groundwater contamination, and energy-intensive processes [22]. Unlike other industries, the space sector has only recently begun to adopt systematic LCA frameworks to evaluate these impacts [23,24].

Regulatory frameworks have not kept pace with the rapid physical and commercial expansion of space activities. The foundational Outer Space Treaty (1967) contains minimal provisions for environmental protection, and more recent guidelines, such as the UN COPUOS Long-Term Sustainability Guidelines, remain voluntary and lack enforcement. As a result, there are currently no binding global standards for launch emissions, reentry safety, debris mitigation, or cumulative environmental impacts in space. A critical implication of this expansion is that space activities are now pressing against planetary boundaries, thresholds that define safe operating spaces for humanity [25]. Once considered outside these limits, the orbital environment and upper atmosphere are now recognized as integral to Earth's climate, atmospheric chemistry, and ecological stability.

The modern space industry has become a major global ecosystem, intersecting with atmospheric integrity, orbital commons, and material sustainability. Orbital commons denotes near-Earth orbital space as a shared, finite resource whose sustainability depends on collective governance and restraint.

As human presence in space expands, the environmental consequences can no longer be overlooked. This review addresses these urgent challenges, aiming to bridge the gap between the optimism of space exploration and the realities of environmental stewardship.

3.2. Environmental Footprint of the Modern Space Industry

The modern space industry exerts environmental impacts across the atmosphere, orbital space, biosphere, and material cycles. Unlike traditional industries, space activities interact with less regulated and poorly understood layers of the Earth system, where even small-scale interventions can have disproportionately large and lasting effects [26]. This review focuses on four primary domains of environmental impact: launch emissions, orbital debris, atmospheric reentry, and light pollution. These domains intersect throughout mission phases and have implications for both planetary systems and sustainability governance.

3.2.1. Rocket Launch Emissions and Atmospheric Effects

Rocket launches have distinct environmental impacts, primarily affecting the stratosphere and mesosphere, regions highly sensitive to chemical and radiative disturbances. Rocket engines emit a complex mix of compounds, including carbon dioxide, water vapor, black carbon, aluminum oxide, nitrogen oxides, and, in the case of solid-fueled boosters, chlorine-based gases. Unlike emissions from aviation or ground transport, these pollutants are injected directly into upper atmospheric layers, where they persist longer and trigger more disruptive chemical reactions [10]. Black carbon from hydrocarbon-fueled rockets is especially concerning, as it absorbs solar radiation and causes localized heating, which can alter ozone chemistry and polar temperature gradients [27,28]. Even a single large launch can deposit significant amounts of black carbon at high altitudes, where removal processes are slow.

Ozone depletion is another major issue, particularly with solid propellant rockets that release reactive chlorine compounds. Although rocket launches currently account for a small fraction of global ozone depletion, the increasing frequency of launches, especially those using solid boosters, could amplify this impact. Methane- and hydrogen-fueled rockets also contribute substantial water vapor, affecting stratospheric humidity and cloud formation [29].

Despite these risks, rocket emissions remain largely unregulated and are not included in national climate inventories or international agreements such as the Kyoto Protocol or Paris Agreement. As launch rates continue to rise, the cumulative effects on upper atmospheric chemistry may become increasingly significant, underscoring the need for targeted mitigation strategies and international oversight [30].

3.2.2. Orbital Debris and the Crowding of Near-Earth Space

The accumulation of anthropogenic debris in Earth orbit constitutes a unique and growing form of environmental pollution. As of early 2025, more than 6,800 operational satellites share orbital space with tens of thousands of tracked debris objects and hundreds of millions of smaller fragments [31]. These range from spent rocket stages and decommissioned satellites to explosion remnants and discarded mission components. Orbital debris presents both environmental and operational hazards. Even small fragments, traveling at orbital velocities, can inflict catastrophic damage on active satellites, space stations, or crewed missions. Collisions generate secondary debris clouds, increasing the risk of further impacts, a cascade effect known as Kessler Syndrome, which could render certain orbital regions unusable for generations [9].

Beyond immediate collision risks, debris contributes to long-term environmental costs. Fragmentation events release trace materials, such as paint particles, lithium, and composite fibers, into orbital trajectories. Some of these particles eventually reenter the atmosphere, while others may persist for decades or even centuries, especially in higher orbits. Despite the severity of the problem, current legal frameworks, such as the Outer Space Treaty (1967) and the Liability Convention (1972), lack effective enforcement mechanisms. Existing mitigation guidelines, including 25-year deorbit policies, are voluntary and inconsistently applied, particularly among emerging space nations and private operators [32,33].

The rapid deployment of satellite mega constellations further amplifies debris risks. With thousands of satellites per operator, even low failure rates can result in significant numbers of uncontrolled objects at congested altitudes. While some constellations use propulsion for controlled deorbiting, anomalies and atmospheric drag fluctuations can lead to premature loss of control. As a result, the orbital environment is shifting from a high-reliability, low-density domain to a complex, high-density system with cumulative and poorly managed externalities [34].

3.2.3. Atmospheric Reentry and Material Fallout

Atmospheric reentry is becoming increasingly frequent as satellite mega-constellations scale, introducing quantifiable material fluxes into the upper atmosphere. Recent estimates indicate that more than 50 metric tons of anthropogenic material reenters Earth's atmosphere annually, a figure projected to rise sharply as thousands of satellites are deorbited per decade. Modeling studies suggest that aluminum-rich components dominate this influx, with measurable deposition in the mesosphere and lower stratosphere. Ferreira et al. [21] estimate that cumulative aluminum deposition from satellite demise may reach levels comparable to natural meteoritic inputs in specific altitude bands, with implications for stratospheric chemistry and radiative balance. However, the temporal persistence, spatial distribution, and chemical transformation pathways of these materials remain poorly constrained, highlighting the need for improved observational datasets and atmospheric modeling integration.

Current estimates suggest that more than 50 metric tons of artificial material reenters the atmosphere annually, a figure expected to rise as mega constellations deorbit thousands of units per decade. Reentry dynamics vary with mass, geometry, materials, and solar-driven drag, producing heterogeneous trajectories and burn-up profiles that complicate modeling and monitoring [35,36]. Unlike meteoritic influxes dominated by silicates, anthropogenic reentry introduces distinct metal and composite signatures whose chemical behavior at high altitudes is not yet well characterized [37].

3.2.4. Light Pollution and Night Sky Degradation

Satellite mega constellations have introduced a new dimension of light pollution: sunlight reflected by large numbers of LEO satellites during twilight contaminates astronomical images and reduces the sensitivity of wide-field surveys. Trailing artifacts complicate calibration, mask faint objects, and can degrade time-domain observations that rely on clean, repeated exposures. Projections for next-generation facilities, such as the Vera C. Rubin Observatory, indicate substantial contamination of wide-field exposures during peak deployment phases, with implications for asteroid discovery, transient astronomy, and cosmology [38].

Ecological impacts extend beyond observatories. Artificial night-sky brightness disrupts circadian rhythms and behavior in nocturnal wildlife and can affect human health. Although individual satellites are often dim, the cumulative effect of thousands of reflective surfaces produces diffuse but persistent luminance across the sky. Mitigation efforts, including darker coatings and visor-equipped designs, have reduced brightness for some models, yet many satellites remain above visibility thresholds under dark skies, and photometric behavior varies across platforms and operational modes.

Governance and technical standards have not kept pace. There are no binding international limits on satellite brightness, reflectivity, orientation, or operational altitudes with respect to night-sky protection. Coordinated monitoring (e.g., public photometric catalogs, standardized observing protocols), design guidelines (surface treatments, baffle geometries, attitude constraints), and deployment practices (altitude selection, constellation phasing to minimize twilight visibility) are needed to protect astronomical and ecological values. Integrating night-sky integrity into licensing and environmental review, alongside debris and emissions considerations, would align orbital operations with broader sustainability objectives and reduce externalities borne by the scientific and ecological commons [39].

3.2.5. Material Footprint and Resource Use in Space Systems

Space systems embody substantial upstream environmental burdens across mining, materials processing, manufacturing, testing, launch, operations, and end-of-life. Satellites and launch vehicles rely on titanium and aluminum alloys, carbon-fiber composites, high-grade steels, rare earth elements (REEs), and lithium-ion batteries, materials selected for strength-to-weight and thermal/electrical performance but produced through energy-intensive supply chains that often externalize environmental costs [40,41]. Extraction and processing of REEs, lithium, and cobalt are frequently concentrated in regions with limited environmental oversight, leading to habitat loss, groundwater contamination, and significant greenhouse-gas emissions; these impacts occur far upstream of launch sites yet are integral to the orbital economy's true footprint [22].

Emerging LCA studies indicate that manufacturing and launch phases dominate the environmental footprint of space missions. For medium-lift launch systems, cradle-to-gate emissions have been estimated to exceed 100,000 kg CO_2-equivalent per mission, with aluminum alloys, carbon-fiber composites, avionics, and propulsion subsystems contributing disproportionately at the satellite level. On a per-kilogram-of-payload basis, these emissions are several orders of magnitude higher than those associated with terrestrial freight transport. When scaled across large constellations, cumulative material throughput and embodied energy shift the space sector from a niche activity to a systemic contributor to global material and energy flows.

End-of-life pathways compound the footprint. Oceanic stage drops and uncontrolled burn-up preclude material recovery, while terrestrial e-waste from obsolete ground equipment lacks standardized dismantling and recycling protocols in many jurisdictions. As production scales from bespoke units to semi-industrial mass manufacture (small-sat batches, frequent launch cadence), embodied energy and raw-material throughput increase, shifting the sector's profile from exceptional to systemic [42]. Yet, LCAs for space missions remain sporadic, methodologically inconsistent, and largely absent from planetary-boundaries discourse and international resource accounting [43].

Despite growing awareness of the material footprint of space systems, several critical challenges persist. First, there is a lack of transparent and openly accessible LCA datasets for common launch vehicles, satellite platforms, and ground infrastructure, which hampers comprehensive environmental accounting. Second, the upstream impacts of mining and materials processing are weakly integrated into mission planning, resulting in overlooked environmental costs. Third, the sector lacks robust standards for material efficiency and circularity, such as design for disassembly, modular upgrades, and component reuse. Fourth, protocols for managing e-waste from space-specific ground assets remain inadequate, contributing to unmanaged terrestrial impacts. Finally, there is no alignment between space industry practices and planetary boundaries indicators or global material footprint metrics, limiting the sector's ability to benchmark and improve its sustainability performance.

To consolidate the thematic insights presented in this section, **Table 1** provides a comparative overview of the five major environmental footprint domains associated with the modern space industry. It highlights the primary sources of impact, associated environmental effects, relative severity, and key knowledge or regulatory gaps.

Table 1. Summary of Key Environmental Footprints of the Modern Space Industry.

Impact Domain	Primary Sources	Environmental Effects	Relative Severity	Key Knowledge & Gaps
Rocket Launch Emissions	Rocket engines (liquid and solid propellants)	Injection of CO_2, H_2O, black carbon, and HCl into stratosphere; ozone depletion; stratospheric heating; localized radiative forcing	High (increasing)	Lack of emission accounting in climate agreements; insufficient modeling of cumulative impacts on ozone and climate
Orbital Debris	Collisions, explosions, abandoned satellites, failed deployments	Collision risk; Kessler Syndrome potential; long-term contamination of orbital altitudes; operational hazards	High	No binding global enforcement for debris mitigation; weak compliance with deorbiting guidelines
Atmospheric Reentry	Satellite and rocket body deorbit and burn-up	Deposition of aluminum, titanium, and other metals in upper atmosphere; possible effects on stratospheric chemistry and radiative balance	Moderate (growing)	Limited empirical studies; no LCA protocols; not integrated into atmospheric chemistry models
Light Pollution	Visible reflectance from satellite mega constellations	Degradation of astronomical observations; disruption of dark sky ecosystems; interference with astrophysics and biodiversity observations	Moderate	No international standards on satellite brightness or reflectivity; lack of environmental governance for visual pollution
Material Footprint	Satellite and rocket production; ground infrastructure; rare earth mining	Resource extraction, energy use, emissions, e-waste generation; impacts in mining regions (water, land, emissions); lifecycle emissions of manufacturing phases	High (overlooked)	Minimal LCA implementation; absent in planetary boundaries discourse; no material efficiency or circularity regulations

3.2.6. Criteria for Assessing Relative Environmental Severity

The "Relative Severity" ratings presented in **Table 1** are based on a qualitative synthesis of four unified criteria derived from the reviewed literature: (i) spatial scale of impact (local, regional, global, or planetary), (ii) persistence and reversibility of environmental effects, (iii) degree of scientific uncertainty combined with potential for irreversible harm, and (iv) regulatory coverage and mitigation maturity. Impact domains rated as "High" are those with global or planetary-scale implications, long persistence times, limited regulatory oversight, and increasing cumulative pressure (e.g., launch emissions and orbital debris). "Moderate" ratings reflect impacts that are significant but more spatially bounded or technologically mitigable, albeit with rising uncertainty under projected growth scenarios. Where noted as "increasing," severity reflects projected launch rates, constellation deployment, and reentry frequency trends reported in recent assessments.

3.2.7. Environmental Implications for Developing and Emerging Space Nations

The environmental impacts of space activities are not evenly distributed, with developing and emerging space nations often bearing disproportionate upstream and downstream burdens. While launch activities are concentrated in a limited number of countries, the extraction of rare earth elements, lithium, cobalt, and other strategic materials essential for spacecraft manufacturing frequently occurs in regions with weaker environmental regulation and enforcement. These activities are associated with habitat degradation, water contamination, and energy-intensive processing, externalizing environmental costs away from launch-benefiting economies.

In addition, emerging space nations seeking entry into the global space economy may face structural barriers to adopting best-practice mitigation technologies, such as controlled reentry systems, active debris removal, or comprehensive LCA reporting, due to cost and technical constraints. The absence of binding global standards risks creating a two-tier sustainability regime, where environmental responsibility is unevenly applied. Addressing these disparities requires capacity building, technology transfer mechanisms, and inclusive governance frameworks that account for development asymmetries while safeguarding shared orbital and atmospheric environments. For example, while agencies such as the European Space Agency and U.S. Federal Communications Commission increasingly incorporate debris-mitigation and end-of-life requirements into licensing, comparable environmental conditions are inconsistently applied across newer spacefaring nations, creating uneven sustainability expectations.

While the environmental impacts reviewed span heterogeneous domains and cannot be directly aggregated into a single metric, a comparative perspective can nevertheless be established using orders of magnitude, spatial scale, persistence, and governance maturity. Launch emissions and orbital debris exhibit global or planetary-scale implications with long persistence and limited regulatory control, whereas reentry material fluxes and light pollution currently manifest as regionally or temporally bounded impacts with high uncertainty but rapid growth trajectories. Material footprint impacts dominate upstream lifecycle stages and scale with constellation size, linking space activities to global material and energy flows. This comparative framing does not imply precise equivalence across domains but enables structured prioritization of risks and research needs.

4. Pathways for Reducing the Environmental Footprint of the Space Industry

As the environmental footprint of the space industry expands across atmospheric, orbital, and terrestrial domains, mitigation pathways must be assessed not only for their environmental potential but also for their technological readiness, scalability, and cost–environment trade-offs. Many proposed solutions remain at experimental or pilot stages, with uneven adoption across operators and jurisdictions. This section evaluates emerging mitigation pathways by considering their current maturity, implementation barriers, and capacity to deliver measurable environmental benefits under projected launch and constellation growth scenarios.

4.1. Greener Launch Technologies

A key mitigation pathway involves the development of low-impact propulsion systems and reusable launch vehicles. Traditional solid and kerosene-based fuels are major sources of black carbon, ozone-depleting substances, and greenhouse gases. In response, the industry is adopting alternative propellants such as liquid methane and liquid hydrogen, which produce less soot and, in the case of hydrogen, emit only water vapor [44]. However, these alternatives present their own challenges: methane is a potent greenhouse gas if leaked, and both fuels require significant energy for cryogenic storage. The effects of increased stratospheric water vapor from these fuels are also not fully understood, and comprehensive life cycle assessments remain scarce [45].

The adoption of reusable launch vehicles marks a more transformative shift. Demonstrated by SpaceX's Falcon 9 and being tested by other providers, reusability reduces material and energy demands per launch and minimizes oceanic stage drops. However, achieving full reusability for all rocket stages remains technically challenging. Looking ahead, experimental concepts such as electromagnetic launch systems and air-breathing scramjets could further reduce reliance on chemical propellants, though these technologies are not yet viable for orbital missions [46,47].

4.2. Satellite Design for Sustainability

Improvements in satellite design offer another route for reducing environmental impact. Several companies and research groups are now incorporating principles of modularity, material efficiency, and responsible sourcing into spacecraft engineering. For example:

- Using bio-based or recyclable materials in small satellite structures.
- Developing modular buses that allow for in-orbit service or upgrades, reducing the need for full replacement.
- Implementing passivation techniques that prevent battery explosions or fuel leaks after decommissioning.

Emerging standards such as the Space Sustainability Rating (SSR), developed by the World Economic Forum in partnership with ESA and the University of Texas at Austin, provide voluntary assessments of satellite sustainability performance based on design, mission profile, collision avoidance capability, and end-of-life planning. These efforts aim to create market incentives for environmentally responsible satellite development, though widespread adoption is still nascent [48].

4.3. Atmospheric Reentry Management

Efforts to mitigate the environmental impacts of atmospheric reentry are still emerging. One approach is to design spacecraft and rocket stages for complete ablation during reentry, minimizing the survival of metallic or composite fragments. Agencies such as NASA and ESA are developing "design-for-demise" protocols to ensure that structural components fragment and vaporize at lower altitudes, reducing the risk of persistent debris. This refers to spacecraft and launch-vehicle engineering approaches that intentionally select materials, structural configurations, and joint designs to ensure complete ablation during atmospheric reentry, thereby minimizing the survival of metallic or composite fragments and reducing long-term atmospheric and ground-level environmental impacts. Additionally, monitoring and modeling of chemical and particulate emissions from reentry events are being advanced through radar, lidar, and high-altitude sampling, although observational capacity remains limited and episodic.

Controlled reentry over remote oceanic zones, such as the South Pacific Ocean Uninhabited Area, is another strategy to prevent debris from reaching populated areas. However, this approach does not address upper-atmosphere pollution and may transfer impacts to poorly understood deep-sea ecosystems. Currently, there are no standardized life cycle assessment protocols for reentry emissions, and funding for comprehensive observational infrastructure is limited. Advancing design-for-demise standards, improving material transparency, and supporting coordinated measurement campaigns are immediate priorities for reducing uncertainty and informing effective regulation [49–51].

4.4. Institutional and Collaborative Pathways

Technological solutions alone are insufficient; institutional innovation and collaboration are essential for effective environmental stewardship in space. Initiatives such as the UN COPUOS Long-Term Sustainability Guidelines, the World Economic Forum's Space Sustainability Rating, and national frameworks like the UK Space Agency's Net Zero Space Commitment offer early-stage mechanisms for aligning industry practices with sustainability goals [52]. Public-private partnerships play a critical role, enabling government agencies to embed environmental criteria in mission contracts, support open LCA data, and fund debris removal infrastructure. Industry actors are increasingly aware of the reputational and operational risks associated with unsustainable practices, especially as Environmental, Social, and Governance (ESG) scrutiny intensifies.

Despite these efforts, the absence of a binding global framework for environmental accountability remains a major barrier. Voluntary codes of conduct, while valuable, are insufficient to ensure equitable and systemic mitigation across jurisdictions. A future global agreement, analogous to the Montreal Protocol or the Paris Agreement, may be necessary to coordinate emissions tracking, debris thresholds, and material sustainability standards in orbit [53]. Advancing institutional collaboration, regulatory harmonization, and transparent reporting will be crucial for transitioning the space sector toward responsible and sustainable growth.

While promising technological and institutional strategies are emerging to mitigate the environmental footprint of the modern space industry, their implementation remains fragmented and largely voluntary. Advances in green propulsion, reusable launch systems, debris mitigation technologies, sustainable satellite design, and collaborative governance frameworks point toward a more responsible orbital future. However, without coordinated global standards, robust environmental assessments, and binding compliance mechanisms, these solutions risk remaining isolated efforts. Achieving meaningful progress will require a paradigm shift, integrating environmental accountability into every stage of space activity and fostering international cooperation to ensure the long-term sustainability of both orbital and terrestrial environments.

5. Research Gaps, Uncertainty, and Limitations

Despite increasing recognition of the space industry's environmental impacts, substantial gaps remain in measurement, modeling, life-cycle accounting, and governance. The lack of transparent, openly accessible LCA datasets for launchers, satellites, and ground systems limits rigorous comparison across fuels, architectures, and mission profiles, while upstream mining and processing impacts are rarely integrated into mission planning. The magnitude and persistence of stratospheric perturbations from rocket soot, alumina, and reentry-derived metals are poorly constrained, underscoring the need for coordinated observation campaigns, controlled experiments, and improved atmospheric modeling.

Debris models often underrepresent constellation-scale dynamics and cascade thresholds, constraining risk-proportionate policy and highlighting the importance of coupling traffic growth and anomaly statistics to probabilistic hazard assessments. The photometric behavior of satellites varies widely, complicating observatory planning and ecological assessment, and there is a clear need for standardized public catalogs and ecological endpoints to inform licensing and deployment guidelines. Material circularity remains nascent, with limited protocols for design-for-disassembly, modular upgrades, and component reuse, and e-waste management for ground assets is inconsistent across jurisdictions.

Orbital congestion and stratospheric integrity are not yet formalized within planetary boundaries or global resource accounting frameworks, and research should focus on developing indicators for orbital commons and upper-atmosphere thresholds that align with material-footprint metrics. Mandatory environmental reporting, including emissions, debris generation, reentry profiles, and LCA summaries, is limited, particularly among private operators, and priorities include public registries, independent audit protocols, and harmonized disclosure formats.

Future research should prioritize methodologically explicit and indicator-based approaches to address identified gaps. Key priorities include: (i) coordinated atmospheric observation campaigns combining lidar, satellite sensing, and in-situ sampling to quantify rocket soot, alumina, and reentry-derived metals; (ii) standardized life-cycle assessment protocols for launch vehicles, satellites, and ground infrastructure aligned with planetary boundaries metrics; (iii) probabilistic debris-cascade modeling that integrates constellation scale, failure rates, and traffic growth scenarios; and (iv) development of measurable orbital sustainability indicators suitable for regulatory benchmarking. Advancing these research directions will enable evidence-based governance and move the field beyond descriptive assessment toward actionable environmental accountability.

Importantly, while the planetary boundaries framework provides a powerful conceptual lens, no agreed quantitative thresholds currently exist for orbital congestion, upper-atmosphere chemical perturbation, or anthropogenic material deposition from space activities. As such, planetary boundaries are invoked here as a heuristic rather than an operational metric. Developing measurable indicators for orbital commons and stratospheric integrity represents a critical frontier for future interdisciplinary research.

6. Conclusion

This systematic review demonstrates that the environmental impacts of the modern space industry are both significant and insufficiently addressed by current regulatory and governance frameworks. As commercial launches, satellite mega-constellations, and reusable spacecraft proliferate, their cumulative effects on atmospheric chemistry, orbital debris, terrestrial resource extraction, and light pollution are becoming increasingly apparent and consequential. Despite the emergence of promising mitigation strategies, such as green propellants, reusable launch vehicles, debris removal technologies, and voluntary sustainability ratings, implementation remains fragmented, voluntary, and largely uncoordinated at the global level.

Persistent research and policy gaps hinder progress toward sustainability. Notably, the lack of transparent, openly accessible LCA datasets, weak integration of upstream mining and material processing impacts, and the absence of robust protocols for material circularity and e-waste management limit the sector's ability to benchmark and improve its environmental performance. Furthermore, the externalization of environmental burdens to regions with limited oversight raises pressing equity concerns that demand interdisciplinary attention.

Addressing these challenges requires a paradigm shift: environmental stewardship and accountability must be embedded into every stage of space activity, from design and launch to operation and end-of-life. Coordinated international frameworks, mandatory environmental reporting, and collaborative innovation across industry, academia, and policy domains are essential to ensure that the space industry evolves from an exceptional frontier to a responsible global ecosystem. Only through systemic alignment and binding standards can the sector safeguard planetary boundaries and support the long-term sustainability of both orbital and terrestrial environments as humanity's extraterrestrial ambitions continue to expand.

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Institutional Review Board Statement

This study is a systematic review based solely on previously published literature, publicly accessible databases, and reports from reputable organizations. No experiments involving humans or animals were conducted, and no confidential, proprietary, or personally identifiable information was used. All sources have been appropriately cited in accordance with academic and ethical standards. The authors affirm that this work complies with the ethical guidelines of the authors' institutions and with the Committee on Publication Ethics (COPE) principles.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data supporting the findings of this study are derived from previously published sources, as cited in the References section. No new datasets were generated during this research. Any additional details regarding the literature search and selection process can be provided by the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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