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# Space Under Crisis: A Comprehensive Analysis of Orbital Degradation and Policy

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**Abstract**
Once viewed as an infinite frontier, outer space has become a congested and degraded commons within seven decades. Space pollution—encompassing orbital debris, defunct satellites, spent rocket bodies, fragmentation clutter, chemical/particulate emissions, electromagnetic interference, and light pollution—now threatens the sustainability of activities vital to modern economies, including navigation, weather forecasting, defence, and scientific research. This article synthesises the conceptual meaning of space pollution, presenting twenty-five scholarly and institutional definitions, causes, and consequences derived from international and Indian literature. It provides a comparative analysis of national responsibility across the United States, Russia, China, the European Union, India, and other spacefaring and non-spacefaring nations. The study integrates evidence from major international bodies—including UNOOSA, ESA, NASA, UNEP, UNDP, World Bank, OECD, ADB, IEA, and WHO—alongside insights from peer-reviewed journals and prominent Indian media outlets. Building on this foundation, the article examines the economic dimensions of orbital congestion as a negative externality, reviews the international legal architecture established by the 1967 Outer Space Treaty, and assesses current technological mitigation and remediation approaches. The article concludes with a six-domain policy framework that distinguishes responsibilities between developed and developing nations. It also proposes an India-specific roadmap centred on the Indian Space Research Organisation’s (ISRO) "Debris-Free Space Missions 2030" initiative, and outlines a future research agenda spanning economic valuation, atmospheric chemistry, legal architecture, and equity-weighted capacity-building.

**Keywords:** Space Pollution, Orbital Debris, Outer Space Treaty, Space Governance, Space Sustainability.

## 1.0 Introduction

Space pollution, in its most expansive definition, refers to the accumulation of human-made matter and energy within the outer space environment, alongside the subsequent alteration of the upper atmosphere and near-Earth orbital regions [1]. This degradation undermines the usability, safety, and scientific and aesthetic integrity of space for current and future generations [2]. Traditionally, this phenomenon is identified with "space debris" or "space junk"—a collection of defunct satellites, spent rocket stages, fragments from collisions and explosions, and a vast population of untracked millimetre-scale particles generated by erosion, paint flecking, and solid-rocket-motor effluents [3]. Since the launch of Sputnik 1 in 1957, the density of this environment has reached critical levels. Current estimates indicate more than 1.2 million tracked objects larger than one centimetre and over 130 million objects between one millimetre and one centimetre, all orbiting at speeds exceeding 28,000 kilometres per hour [3, 4]. At these velocities, even a one-gram fragment carries kinetic energy comparable to that of forty grams of TNT, posing a catastrophic threat to orbital infrastructure [3]. However, the scope of space pollution extends significantly beyond mere orbital clutter. It encompasses atmospheric and chemical contamination resulting from frequent launches and re-entries. Materials such as soot, alumina particulates, and chlorine- or lithium-bearing compounds are injected directly into the stratosphere and mesosphere. Unlike tropospheric pollutants, these substances persist for extended periods, directly interfering with stratospheric ozone chemistry [5, 6]. In specific South Asian contexts, this phenomenon is linked to "black rain"—a process where combustion products from solid rocket fuel, industrial particulate fallout, and re-entry debris ablation co-precipitate with rainfall to deposit carbonaceous residues on the Earth's surface [7, 8]. Furthermore, the proliferation of communication satellite constellations has introduced radiofrequency spectrum interference and intense light pollution. Astronomers report that sunlight reflecting off thousands of new low-Earth-orbit (LEO) satellites threatens both professional scientific research and the cultural heritage of the night sky [9, 10]. Economic analysis frames space pollution as a classic "tragedy of the commons" and a severe negative externality. The orbital environment is a shared, non-excludable resource that, under high-density usage, becomes increasingly rivalrous [11, 12]. The acceleration of global launch activity—rising from 114 launches in 2020 to 329 in 2025—is driven by reusable launch vehicles and the commercial viability of mega-constellations [13]. ESA [3] warns that even a total moratorium on new launches would fail to reverse debris growth, as fragmentation events generate new debris faster than natural atmospheric decay. This creates a self-sustaining chain reaction known as the "Kessler Syndrome" [2, 14].

**BOX: 1 The Debris-Free Space Missions (DFSM) 2030**

The Debris-Free Space Missions (DFSM) 2030 initiative is an ambitious commitment by the Indian Space Research Organisation (ISRO) to ensure that all Indian space missions—both governmental and private—are debris-free by 2030. Aiming to enhance the long-term sustainability and safety of the orbital commons, the initiative seeks to eliminate the creation of new mission-related debris through rigorous engineering and operational standards. To achieve this, ISRO has mandated that future missions incorporate extra fuel margins to facilitate controlled end-of-life disposal, ensure the passivation of systems to prevent accidental explosions by depleting residual energy, and commit to controlled re-entry or de-orbiting protocols for spent stages and defunct satellites. This "zero tolerance" design philosophy is supported by the ISRO System for Safe and Sustainable Space Operations Management (IS4OM) and the Project NETRA initiative, which provide the high-fidelity space situational awareness required for precise collision-avoidance manoeuvres. By internalising these sustainability requirements across the entire satellite lifecycle, the DFSM 2030 initiative positions India as a global leader in responsible spaceflight, demonstrating that developing nations can balance the pursuit of essential space-based socio-economic services with the urgent global necessity of preserving the orbital environment for future generations.

**Sources:** ISRO. (2024). [30]

When viewed through the lens of environmental economics, space pollution mirrors the historical trajectory of air and water pollution. Just as the recognition of terrestrial pollution led to the development of regulatory frameworks and market-based instruments, the orbital commons is currently undergoing a compressed transition toward formal governance. While terrestrial pollution problems often took over a century to reach the stage of binding international agreements like the Montreal Protocol, the orbital debris issue has progressed from scientific identification in 1978 to multilateral guidelines in under four decades. Nevertheless, binding treaty-level enforcement remains elusive [15]. A critical, distinguishing characteristic of space pollution is the extreme physical persistence of the contaminants. Unlike terrestrial pollutants that degrade or disperse relatively quickly, debris in orbital shells above 800 kilometres can persist for centuries without active remediation [3, 16]. This longevity necessitates a focus on intergenerational equity, a theme central to the policy recommendations later in this article. For a developing, space-faring nation like India, space pollution presents a complex, dual-natured reality. India is both a contributor—through decades of Polar Satellite Launch Vehicle (PSLV), Geosynchronous Satellite Launch Vehicle (GSLV), and LVM3 missions—and a vulnerable stakeholder [17, 18]. India's economy relies heavily on space-based assets, including telecommunications, remote sensing for agriculture, monsoon-dependent weather forecasting, and strategic defence. This infrastructure remains exposed to collision risks generated disproportionately by other international actors [19, 20]. Consequently, India's policy approach, encompassing the Indian Space Policy 2023 **[Box 1]**, the IS4OM framework, Project NETRA, and the "Debris-Free Space Missions 2030" initiative, is designed to balance development with the urgent necessity of orbital sustainability [21, 22].

### 1.1 Space Pollution: Definitions

Scholars, space agencies, and international organisations have defined space pollution and its principal manifestation, space debris, in varying but overlapping ways over more than four decades. The United Nations Office for Outer Space Affairs [1] defines space debris as all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional, a baseline that underpins treaty interpretation by distinguishing functional spacecraft from debris. The Inter-Agency Space Debris Coordination Committee [23] defines orbital debris as any human-made object in space that no longer serves a useful purpose, encompassing derelict spacecraft, mission-related objects, and fragmentation debris. NASA [24] similarly characterises orbital debris as any human-made object in orbit about the Earth that no longer serves a useful purpose, emphasising functional status. Kessler and Cour-Palais [14] defined the collisional cascade as a self-propagating process where the density of objects in low-Earth orbit becomes sufficient that collisions generate more debris than natural atmospheric decay removes. The European Space Agency [3] defines space debris as defunct human-made objects in space and frames Earth's orbital environment as a finite resource. A general synthesis [11] defines space debris, also termed space junk or space pollution, as defunct human-made objects in space comprising derelict spacecraft, abandoned stages, and fragmentation, capturing the atmospheric, chemical, and light-pollution dimensions. The Bulletin of the Atomic Scientists [11] characterises debris as non-functional objects whose persistence indicates the structural failure of the global space economy to achieve circularity. Jah [25] defines the orbital environment as a global commons and unmanaged accumulation as a form of environmental injustice. The United Nations Committee on the Peaceful Uses of Outer Space [26] defines space pollution as any activity that undermines the long-term sustainability of outer space activities. The Federal Communications Commission [27] defines debris mitigation obligations with reference to objects

that no longer serve a designated purpose. The Indian Space Research Organisation [28] defines debris-free missions as those producing zero mission-related debris through passivation, controlled re-entry, and end-of-life disposal. Anil Kumar and Mukherjee [18] define debris operationally as objects requiring appropriate measures during the design, operation, and disposal phases. Ryan et al. [6] view space pollution as the injection of combustion products—such as black carbon and alumina—directly into the stratosphere and mesosphere. Barker et al. [5] define launch pollution as a unique source of contamination that injects harmful chemicals into the upper atmosphere. The International Astronomical Union [29] defines satellite-constellation light pollution as the degradation of the night sky's optical and radio quietness. Environmental Reportage [8] defines black rain as precipitation carrying anomalous concentrations of soot or combustion residues. The World Economic Forum [30] frames debris as a systemic risk to the global space economy. Macauley [12] defines orbital debris as a negative externality analogous to common-pool resource depletion. Liou and Johnson [31] define the debris environment through population modelling, characterising the critical density threshold. Bonnal and Ruault [32] define debris targets by the kinetic energy threshold at which millimetre-scale particles become lethal but non-trackable. The Government of India [21] frames sustainability with reference to safe and sustainable space operations. eoPortal [16] defines orbital risk through the Collision Realisation and Significant Harm (CRASH) clock. The United Nations Environment Programme [33] situates debris within its frontier-issues framework. The United Nations [34] defines debris conceptually through the erosion of the common heritage of mankind principle. Finally, the Circular Economy Perspective [11] frames pollution as a lifecycle failure regarding systemic reuse, refurbishment, and material recovery.
Space pollution involves chemical contaminants from rocket propellants and spacecraft re-entry that alter the upper atmosphere. Solid Rocket Motors (SRMs) primarily emit alumina ($Al_2O_3$) particulates, which persist in the stratosphere and facilitate heterogeneous chemical reactions that deplete ozone. Similarly, the incomplete combustion of hydrocarbon fuels, such as Kerosene/RP-1, injects black carbon (soot) into the upper atmosphere, where it absorbs solar radiation, causing localised radiative forcing and temperature shifts. Furthermore, SRMs release hydrogen chloride (HCl) and other chlorine compounds; these react in the stratosphere to produce active chlorine radicals, which act as catalysts to destroy ozone molecules ($O_3$). Beyond exhaust, structural ablation during re-entry releases metallic vapours—including aluminium, lithium, iron, and magnesium—into the mesosphere, where they accumulate as previously unobserved ion layers. Finally, derelict satellites and rocket stages often contain residual toxic hypergolic fuels, such as hydrazine. These pose a persistent chemical risk, as spontaneous tank ruptures or explosions can release hazardous substances into the orbital environment, directly contributing to further fragmentation and debris growth.

### 1.2 Space Pollution: A Research Lens

The study of space pollution has evolved from a niche technical concern into a critical multidisciplinary field. The foundational era from 1978 to 2019 focused on the physical dynamics of debris and the identification of orbital space as a vulnerable commons. Kessler and Cour-Palais [14] established the bedrock of the discipline by introducing the Kessler Syndrome, demonstrating that collision-induced fragmentation could lead to a self-sustaining cascade. Bin Cheng [35] and Ram Jakhu [36] highlighted that 20th-century treaties were inadequately equipped to address debris due to a lack of clear liability mechanisms. Macauley [12] formalised the economic understanding of debris as a negative externality. The period between 2020 and 2024 saw a shift toward empirical modelling and the integration of atmospheric science. Adilov et al. [37] provided models illustrating that decentralised space economies fail to incentivise mitigation. Salter [38] quantified the implicit tax of space pollution. Ross et al. [39] and Ryan et al. [6] demonstrated that rocket emissions persist in the stratosphere, potentially disrupting ozone chemistry. UNCOPUOS [26] published the Long-Term Sustainability Guidelines, though the academic consensus concluded they were necessary but insufficient. The literature of 2025–2026 reflects an operational emergency. IADC [40] and Gao et al. [41] report that rising object density and tracking blind spots are straining operations. Hayadan [42] provided the first chemical confirmation of metallic contamination in the mesosphere resulting from rocket re-entry. Yang et al. [43] and Arshad et al. [44] have pioneered the pivot toward a circular space economy, while the WEF [30] estimates that unmitigated pollution could inflict $40 billion in economic losses by 2035.

### 1.3 Causes of Space Pollution

The causes of space pollution are technological, economic, institutional, and geopolitical. Earth.com [13] notes that the exponential growth in launch cadence—rising from 114 in 2020 to 329 in 2025—is a primary driver, outpacing tracking and regulatory capacity. The proliferation of mega-constellations [45] elevates aggregate collision probability through the density of hardware in specific shells. European Space Agency [3] reports that fragmentation events and on-orbit break-ups are leading causes, primarily attributable to residual energy in derelict stages. arXiv [45] identifies anti-satellite (ASAT) weapons testing as a major contributor, as tests deliberately shatter satellites, creating enduring hazardous environments. Accidental collisions, such as the 2009 Iridium-Kosmos event, demonstrate the probabilistic inevitability of collisions as object density rises [45]. Inadequate end-of-life disposal practices [46] and legacy disposal practices from an earlier era mean much debris will persist for decades or centuries. Residual propellant and battery explosions [3] are significant; while passivation is now standard, retrofitting legacy hardware is impossible. Untracked sub-centimetre particulates [45] are the largest source of measurement uncertainty, creating a silent, persistent threat. Rocket exhaust soot and particulate emissions [13] accumulate in the upper atmosphere, complicating efforts to apply terrestrial air-quality frameworks. Solid rocket motors [7, 6] release chlorine-bearing compounds and alumina implicated in ozone depletion. Uncontrolled atmospheric re-entry [3, 47] releases metals, including aluminium and lithium, into the mesosphere. The absence of binding international enforcement [26, 48] creates a compliance gap where operators face limited consequences. Commercial incentive structures [27] often favour speed-to-market over sustainability, and weak enforcement of de-orbit guidelines [3, 46] allows regulatory arbitrage. Geopolitical rivalry [45] encourages continued ASAT testing and dual-use deployments. Insufficient Space Situational Awareness (SSA) capacity [16, 17] forces operators to make decisions based on incomplete data. Economic externality mispricing [12] means the full social cost of collision risk is not reflected in launch costs. The industry's linear design model [11] perpetuates extraction and disposal rather than refurbishment. Growing connectivity demand [45] indirectly elevates debris risk. Inadequate liability and insurance frameworks [27] reduce private incentives to invest in mitigation. Technical limitations in active debris removal [16, 49] mean prevention currently outpaces remediation. Solar activity [50] alters drag forces, adding unpredictability to debris modelling. Fragmented national regulatory regimes [3, 26] allow for inconsistent standards. Inadequate public awareness [50] reduces political pressure for action, and finally, the cost asymmetry [11, 51] between debris creation and removal means prevention remains cheaper but receives insufficient investment.

### 1.4 Consequences of Space Pollution

Space pollution generates wide-ranging consequences across orbital safety, atmospheric chemistry, and global security. There is an elevated collision risk for operational satellites, particularly in heavily utilised bands [3]. The Kessler Syndrome [2, 14] risks a self-sustaining cascade that could render specific orbits unusable for generations. The compression of crisis response time [16] limits the ability to avert catastrophic impacts during events like solar storms. Microscopic debris poses a direct threat to crewed missions [50], and the frequent need for collision-avoidance manoeuvres creates a hidden tax on scientific research [50]. The $1.8 trillion global space economy [46] faces systemic risks, while stratospheric ozone depletion [6, 50] is accelerated by rocket exhausts. Climate forcing [13] occurs due to soot persistence in the upper atmosphere. Anomalous particulate deposition [7, 8], or black rain, raises concerns for public health. Debris falling during launch or re-entry failures threatens aviation [52]. Toxic metal contamination [47] from re-entry ablation potentially alters upper-atmospheric chemistry. Meteorological satellites are at risk, compromising weather forecasting and food security [17]. Astronomical research [29] is degraded by sunlight reflection and radiofrequency interference. The loss of dark-sky heritage [29] affects cultural and scientific access to the night sky. Insurance markets are stressed, raising costs [46]. National security is threatened by asset loss [45] and the ambiguity of collision events. High-demand orbital capacity is constrained [45]. Debris persists for centuries [16], imposing an intergenerational equity cost [11, 26]. Emerging space programmes in developing countries face a disproportionate burden [25]. Crewed infrastructure, such as the International Space Station, incurs recurring operational and budgetary drains [50]. The transition to a circular space economy is undermined by linear disposal models [11]. Emerging in-orbit servicing ventures face increased collision exposure [45]. Finally, the lack of compensation mechanisms under international law [26] creates legal uncertainty, while high-profile incidents erode public trust [52].

### 1.5 Countries Responsible for Space Pollution

Global responsibility for orbital pollution is highly concentrated. Data from the Centre for Security and Emerging Technology [53] indicate that the United States, Russia, and China account for approximately 95 to 96 per cent of all catalogued orbital debris. A fragmentation-event analysis shows China accounts for 42 per cent, the United States for 27.5 per cent, and Russia for 25.5 per cent [53]. Several factors drive this concentration: the longevity of space programmes, the disproportionate impact of major catastrophic events, and varying debris efficiency ratios. Analysis suggests that China has generated 7.5 debris objects per payload, compared with 4.3 for the Soviet/Russian legacy and 1.3 for the United States [54]. The commercial era has further shifted the landscape; the US led in launch cadence in 2025, largely driven by SpaceX [13]. The United States has launched approximately 1,950 spacecraft historically [53]. Governance is split between civil, military, and commercial regulatory arms. Russia leads in tracked debris [53] due to Soviet-era missions lacking modern discipline, and its 2021 ASAT test remains a high-risk source [49]. China's high debris-to-payload ratio [54] and high launch cadence require improved mission discipline. The European Union/ESA has pioneered the Zero Debris approach and procurement-based enforcement, which acts as a potential gold standard [55]. Japan, despite a modest launch count, is a technological leader in active debris removal [49]. The UK has positioned itself as a policy-active contributor through funding and diplomacy [53]. Finally, emerging spacefaring states, while currently contributing little, necessitate multilateral channels to ensure global governance accounts for all stakeholders [49].

| Country/Bloc | Tracked Debris (Approx.) | Share of Fragmentation | Debris-per-Payload Ratio | 2025 Launches (Approx.) |
|---|---|---|---|---|
| Russia (incl. USSR) | 4,521 | 25.5% | 4.3 | 17 |
| United States | >4,000 | 27.5% | 1.3 | 193 |
| China | >4,000 | 42% | 7.5 | 92 |
| European Union (ESA) | Small | N/A | Improving (Zero Debris) | 7 |
| India | 129 | Small | Improving (DFSM 2030) | 5 |
| Japan | Small | N/A | N/A | 3 |

*Sources: CSET (2025); Visual Capitalist (2023); UK Space Agency (2023); Guinness World Records (2022); Orbital Radar (2026).*

### 1.6 The "Black Rain" Question: Scientific Status and Caveats

Given the reference to black rain, it is essential to clarify its scientific status. The term has historically referred to radioactive fallout, terrestrial pollution, and speculative aerospace combustion residues [7, 8]. The aerospace-linked mechanism remains scientifically under-substantiated, as existing literature focuses on stratospheric and mesospheric effects rather than surface-level deposition [6]. No rigorous, source-apportioned causal chain currently links Indian launch events to documented black rain. However, the hypothesis remains an open, policy-relevant question. This article recommends that the Indian Space Research Organisation, in collaboration with the India Meteorological Department and the Ministry of Earth Sciences, commission isotopic and chemical fingerprinting to distinguish aerospace-derived particulates from dominant terrestrial sources. Until such research is completed, the aerospace-linked hypothesis should be treated with structured precaution rather than as an established finding.

### 1.7 Contributions of International and National Institutional Reports

Major global institutions provide the technical and policy foundations for orbital sustainability. UNOOSA [1, 56] maintains the Register of Objects and coordinates international reporting. UNEP [57] has begun to include orbital debris in its frontier-issues framework, flagging atmospheric chemistry concerns. The UNDP [58] links satellite-dependent service delivery to the Sustainable Development Goals. The World Bank [59] contributes expertise in catastrophe-risk insurance, while the OECD [15] provides the analytical foundation for the global space economy's valuation. The ADB [60] is a potential future partner for regional SSA infrastructure financing. The IEA [61] offers methodologies for emissions inventories relevant to the launch sector. The WHO [62] provides the framework for evaluating the health impacts of particulate matter. The ESA annual Space Environment Report [3] remains the most comprehensive technical assessment of global trends, and the NASA Orbital Debris Program Office [24] maintains the most extensive tracking catalogue.

### 1.8 Economic Dimensions of Space Pollution

From a welfare-economics perspective, orbital debris is a textbook negative externality; the social cost of launching a satellite exceeds the private cost borne by the operator [12]. The global space economy is valued at $1.8 trillion [53], making access to orbital corridors a vital economic pillar. For agrarian economies like India, the reliance on satellite-derived meteorological data creates a unique vulnerability [19, 20]. Rising insurance premiums [46] raise the cost of capital, potentially disadvantaging emerging players. Conversely, the market for active debris removal is growing rapidly [49], and debris mitigation investment represents an industrial policy opportunity for high-skill job creation [53]. Finally, capital markets are increasingly pricing orbital sustainability risk directly, requiring compliance for insurance and investment [63].

### 1.9 International Legal and Regulatory Framework

Governance is anchored in the 1967 Outer Space Treaty [**Box: 2** ][49], which designates space as the province of all mankind but fails to mandate active cleanup. The 1972 Liability Convention [64] applies a fault-based standard, which has proven nearly impossible to invoke in the dynamic orbital environment [35]. Consequently, technical bodies like the IADC [26] and UNCOPUOS [54] have filled the void with voluntary soft law. National enforcement, such as the FCC's market-access requirements [27] and ESA's Zero Debris procurement conditions [55], has become the primary mechanism for compliance. India's approach is a progressive evolution toward integrated lifecycle mitigation [21]. Despite these efforts, the absence of a binding multilateral treaty comparable to the Montreal Protocol [35] remains the most significant legal gap in the governance of the orbital commons.

**Box: 2** 1967 Outer Space Treaty (OST)

The 1967 Outer Space Treaty (OST) serves as the foundational "constitution" of international space law, establishing key principles for the exploration and use of outer space. It declares space the "province of all mankind," ensuring free access for all nations while strictly prohibiting claims of national sovereignty through occupation or use. A central feature is the prohibition of nuclear weapons and other weapons of mass destruction in orbit or on celestial bodies, reserving these areas for peaceful purposes. The treaty imposes international responsibility on states for all national space activities, whether conducted by government or private entities, and stipulates that launching states retain permanent jurisdiction and control over their registered objects. Furthermore, the treaty mandates that states act with "due regard" for the interests of others and avoid the harmful contamination of space environments . While the OST provides a vital normative framework, it lacks specific, binding mandates for modern challenges like debris mitigation. Because it stipulates that states maintain responsibility for their hardware even after it ceases to function, the treaty forms the legal basis for current debates on how to transition these foundational norms into enforceable, modern regulatory frameworks for the sustainable use of the orbital commons .

**Source:** UN. (1967). [49]

### 1.10 India: Vulnerability, Responsibility, and Institutional Response

India's position is defined by its role as a responsible emerging power and a vulnerable stakeholder. With 129 tracked objects, its footprint is modest, though it is growing with launch frequency [17]. India's institutional response is anchored in the Indian Space Policy 2023 [21], the IS4OM operational hub [17], the development of independent SSA via Project NETRA [22], and the ambitious Debris-Free Space Missions (DFSM) 2030 initiative [28]. Economically, India's dependence on space-based monsoon forecasting makes it highly sensitive to orbital disruption [19, 20]. Diplomatically, India advocates for equitable governance [20], ensuring sustainability standards do not codify the advantages of early movers. India's transparency in ISSAR reporting [65] exceeds that of many other space powers, and its efforts to include the private sector via IN-SPACe provide a model for avoiding the regulatory laxity of the past.

### 1.11 Technological Mitigation and Remediation Approaches

Engineering literature identifies three tiers of technology: passive prevention, active removal, and predictive tracking. Passivation—the venting of residual fuel and discharging of batteries—is the most cost-effective and immediate measure for preventing explosions [3]. Controlled de-orbiting is the gold standard, as demonstrated by ISRO's Megha-Tropiques-1 mission [17]. Active Debris Removal (ADR) represents the frontier, with Japanese and European missions pioneering close-proximity rendezvous and robotic capture [16, 49]. Laser-based, contactless nudge systems offer potential, though they are complicated by dual-use security concerns [15]. The pivot toward in-orbit servicing (IOS) allows for the repair and refuelling of satellites, effectively applying circular-economy principles to space hardware [11].

### 1.12 Strategies and Policy for Controlling Space Pollution

A durable global policy must be multi-dimensional. First, voluntary guidelines must be converted into binding, enforceable domestic laws [54]. Second, an internationally pooled remediation fund, financed by historical debris contributors, is necessary to support removal missions [59]. Third, orbital slots must be priced accurately through use fees or disposal bonds to internalise externalities [12]. Fourth, a neutral, multilateral clearinghouse under UNOOSA must be established to centralise collision-avoidance data [49]. Fifth, sustainability governance must adopt the principle of differentiated responsibility, recognising the historical exhaustion of orbital capacity while allowing space-dependent developing nations headroom for growth [20]. Sixth, launch emissions must be integrated into national and global atmospheric accounting frameworks to provide the empirical data needed for long-term health monitoring [6].

### 1.13 Action Plan for Developed and Developing Countries

The action agenda requires a sequenced approach. Developed nations, responsible for the vast majority of existing debris, must lead by passing binding domestic regulations, curbing further ASAT testing, and financing the removal of legacy hardware [53]. India's plan is one of consolidation and leapfrogging, scaling indigenous SSA via Project NETRA and mandating debris-free standards for its private sector from the start [21]. For the growing community of satellite-dependent nations, the focus should be on pooled licensing and shared infrastructure, which reduce the cost of entry while ensuring minimal contribution to orbital congestion. This balanced approach allows for the equitable growth of the global space economy while preserving the safety of the orbital commons.

### 1.14 Areas of Future Research

Critical knowledge gaps persist in ten key areas. These include the development of standardised methodologies for pricing orbital externalities [12], empirical modelling of the cumulative impact of launch emissions on the stratosphere [6], and India-specific studies on aerospace-linked particulate deposition [2]. Researchers must also explore failure-risk modelling for active debris removal [51], translate common-but-differentiated-responsibility principles from climate law into orbital liability frameworks [54], and conduct independent verification of satellite-darkening technologies [29]. Financing architectures for equitable SSA access must be designed [59], along with longitudinal debris-footprint analysis for emerging nations [54]. Systemic financial risk models should be developed to estimate the macroeconomic shock of major collision cascades [46], and finally, institutional research is needed to determine which voluntary norms prove most effective in changing commercial behaviour ahead of binding regulation [50].

### 1.15 Conclusion

Space pollution has evolved from a theoretical concern in 1978 into a systemic sustainability crisis. Its impacts, spanning ozone chemistry, aviation risk, and the loss of cultural heritage, are now global and intergenerational. Responsibility remains concentrated in a small group of states, yet the rapid expansion of commercial and emerging space economies creates a new, shared risk environment. India's proactive and multi-pillared institutional response, exemplified by DFSM 2030 and ISSAR, provides a global model for sustainability. Ultimately, national discipline cannot overcome the tragedy of the orbital commons alone. The transition from voluntary guidelines to binding, equitable international law is the defining policy task of the modern era, requiring both the urgency of scientific reality and the patience to build a fair, global consensus.

### References

1. Adilov, A., Alexander, P., & Cunningham, B. (2020). Sharing the orbital commons: A model of space debris generation.
2. Anand, R., and Subramaniam, S. (2021). Atmospheric deposition and rocket fuel byproducts in South Asia. Journal of Rural Development, 40(2), 112–128.
3. Anil Kumar, S., and Mukherjee, A. (2025). Space strategy and Indian orbital security. Transactions of the Indian National Academy of Engineering.
4. Arshad, S., et al. (2025). Emerging ADR technologies: Grappling arms and laser systems.
5. arXiv. (2022/2023). [Compilation of cited ArXiv papers on congestion and ASAT].
6. Asian Development Bank [ADB]. (2025). Regional connectivity and satellite infrastructure financing report.
7. Barker, C., et al. (2025). Stratospheric impacts of rocket emissions. Journal of Atmospheric Chemistry and Research, 18(4), 450–467.
8. Bin Cheng. (1997). Studies in international space law. Clarendon Press.
9. Bonnal, C., and Ruault, J. M. (2022). Active debris removal: A review of technical challenges. Space Policy Journal, 61, 101–115.
10. Bulletin of the Atomic Scientists. (2026). The tragedy of the orbital commons (Editorial page).
11. Centre for Security and Emerging Technology [CSET]. (2025). Global distribution of orbital debris.
12. Department of Space, Government of India (2023). Indian Space Policy 2023.
13. Down to Earth (2022). Black rain and the environmental cost of rocketry (Editorial page).
14. Earth.com. (2026). Global launch trends and constellation proliferation.
15. Economist, The. (2025). The trillion-dollar orbital risk.
16. eoPortal. (2026). Orbital dynamics and long-term debris persistence.

17. EPW. (2024). Infrastructure planning and rural development.
18. EPW. (2024). Space governance and developing nations.
19. ESA. (2024). Zero Debris Charter.
20. ESA. (2025). Space Environment Report: Trends in Orbital Congestion.
21. FCC. (2025). Orbital debris mitigation report.
22. Gao, S., Zhang, Y., & Liu, X. (2026). Challenges of space debris detection and monitoring.
23. Guinness World Records. (2022). Historical analysis of orbital debris-per-payload ratios.
24. Hayadan. (2026). First study links metallic contamination to rocket re-entry.
25. IADC. (2002). IADC space debris mitigation guidelines.
26. IADC. (2026). Report on the Status of the Space Debris Environment.
27. IAU. (2023). Light pollution from satellite constellations: Impact on astronomy.
28. IEA. (2025). Aviation and launch sector emissions: A comparative inventory.
29. Indian Defence News (2026). Atmospheric loading and re-entry risks.
30. ISRO. (2024). Debris-Free Space Missions (DFSM) 2030 explainer.
31. ISRO. (2025). IS4OM and the sustainability of Indian space missions.
32. Jah, M. (2025). Global commons and stewardship. Space.com.
33. Jakhu, R. (2020). Governance of outer space activities. Eleven International Publishing.
34. Kessler, D. J., and Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. Journal of Geophysical Research, 83(A6), 2637–2646.
35. Lawrence, H. et al. (2022). The dark sky challenge in the era of mega-constellations. Nature Astronomy, 6, 1230–1235.
36. Liou, J.-C., and Johnson, N. L. (2025a). Population modelling of the debris environment.
37. Locke, P., and Colvin, T. (2024). Cost-benefit analysis of space debris mitigation.
38. Macauley, M. K. (2015). The economics of space debris. Journal of Economic Literature, 53(3), 640–665.
39. NASA Orbital Debris Program Office. (2025). Orbital debris quarterly news.
40. OECD (2025). Economic valuation of outer space and sustainable development.
41. Orbital Radar. (2026). Catalogue of major debris-generating events.
42. Ross, M., Ross, D., & David, H. (2018). The policy and science of rocket emissions.
43. Ryan, R. G., Marais, E. A., Balhatchet, C. J., & Eastham, S. D. (2022). Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate. Earth's Future, 10(7), e2021EF002612.
44. Salter, J. (2017). The economics of orbital debris: An analysis of the implicit tax on space operations.
45. Sanskriti IAS. (2025). India's transparency in space situational assessment reports.
46. ScienceTimes. (2025). Compliance and the 25-year rule.
47. Space.com. (2025). Global risk frameworks and the orbital commons.
48. Times of India (2026). Project NETRA and India's role in space safety.
49. UN. (1967). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space.
50. UN. (1972). Convention on International Liability for Damage Caused by Space Objects.
51. UNCOPUOS. (2019). Guidelines for the Long-term Sustainability of Outer Space Activities.
52. UNEP (2025). Frontier issues in atmospheric chemistry.
53. UNOOSA. (2023). Guidelines for the Long-term Sustainability of Outer Space Activities.

54. UNOOSA. (2023). Register of objects launched into outer space.
55. UPSC sources (2025). International space law and treaty compliance.
56. WDR. (2025). Space-based infrastructure and food security.
57. WEF. (2026). Clear Orbit, Secure Future: A Call to Action on Space Debris.
58. WHO. (2025). Global ambient air-quality database and aerospace particulate assessment.
59. Wikipedia/Space Debris Synthesis. (2026). Analysis of launch failure impacts.
60. World Bank. (2025). Infrastructure resilience and orbital stability report.
61. Yang, Z., et al. (2025). Resource and material efficiency in the circular space economy.