ISSN: 2393-8048
International Advance Journal of Engineering, Science and Management (IAJESM)
Multidisciplinary, Multilingual, Indexed, Double Blind, Open Access, Peer-Reviewed, Refereed-International Journal.
SJIF Impact Factor =8.152, January-June 2025, Submitted in February 2025

Space Debris and Environmental Sustainability: Legal Obligations and Future Governance Models

Dr. Ashis Kumar Mukhopadhyay, Department of Law, 4/2, Monmohan Mukherjee Road, P.O. & P.S. - Bally, Dist. – Howrah, West Bengal – 711201, akm.lawsolution@gmail.com

Abstract

Earth's orbital environment is getting more crowded and dirty with space junk. This puts important satellite services at risk and raises serious questions about how to protect the environment beyond Earth. There are already duties in international space law that can be used to deal with debris. These include "due regard" duties, harmful contamination avoidance duties, and consultation duties. However, these rules are still very general and not very easily enforced. At the same time, local regulators and non-binding international guidelines have become the main tools for governance. This has led to a disorganised system that has trouble managing the size of mega-constellations, servicing them in orbit, and removing active debris (ADR). This paper takes a look at the current legal obligations that apply to space junk, judges their limits in terms of environmental sustainability, and suggests new ways to govern the space junk problem. These include making the laws stronger without making them more strict, using treaties to govern "orbital environmental" issues, changing how people are responsible for accidents, and setting up institutions for space traffic management (STM). The paper uses recent data on debris and regulatory trends to make the case for a hybrid governance architecture that includes (i) minimum performance standards that are enforced through national licensing, (ii) internationally harmonised STM rules and data-sharing, (iii) an incentive-compatible economic layer (fees, insurance, bonding), and (iv) a legitimacy layer through the UN system to make sure that everyone has equal access to orbital commons and less fragmentation.

Keywords: Space debris, sustainability, Outer Space Treaty, liability, Space traffic management, Governance, Orbital commons, Active debris removal.

1. Introduction

Orbital space is now widely recognised as a finite and vulnerable environmental resource, similar to other global commons such as oceans and the atmosphere. Over the past two decades, space activity has expanded rapidly, particularly due to the deployment of large satellite constellations for communication, navigation, Earth observation, and defence. This rapid growth has significantly increased orbital congestion and the likelihood of accidental collisions. According to assessments by the European Space Agency, nearly 40,000 objects are currently tracked in Earth orbit, while only about 11,000 are active satellites, indicating a sharp imbalance between operational assets and non-functional debris [1]. Scientific modelling and long-term monitoring consistently warn that the debris population is growing faster than it is being removed, raising the risk of cascading collision events that could render key orbital regions unusable for future missions. This trend poses a serious challenge to the long-term sustainability of outer space activities. Studies conducted between 2018 and 2023 show that Low Earth Orbit has become particularly congested due to the concentration of satellites at similar altitudes. Satellite operators increasingly report frequent close-approach warnings, forcing collision-avoidance manoeuvres that consume fuel, reduce satellite lifespan, and increase operational costs [2]. These risks are not confined to individual operators; instead, they affect all current and future users of space. As a result, space debris must be understood not merely as a technical or engineering problem, but as an environmental governance issue involving shared resources, intergenerational equity, and the unequal distribution of risk and responsibility. International space law, however, was developed during an era when space activities were dominated by a small number of states engaged mainly in exploration and geopolitical competition. Foundational treaties emphasised state responsibility and liability but did not anticipate today’s commercialised, congested, and technologically complex orbital environment. Although existing legal instruments establish important principles such as due regard, liability for damage, and international cooperation, they do not provide clear, enforceable standards for debris mitigation, satellite disposal, or collision risk management. Consequently, practical debris control has largely shifted to non-binding international guidelines and domestic licensing regimes, which differ widely across states [3]. This has created a significant governance gap. While space debris generates collective and cumulative harm affecting the entire orbital environment, regulation remains fragmented and individualised, with compliance assessed on a state-by-state and operator-by-operator basis. Surveys of national regulatory frameworks indicate that advanced spacefaring nations have strengthened debris mitigation requirements, while many emerging space actors lack comparable regulatory capacity or enforcement mechanisms. Such fragmentation allows risk externalisation, where the environmental costs of space activities are not fully borne by those who create them. This imbalance has led to growing calls among scholars and policymakers for a shift toward integrated environmental governance models that treat orbital space as a shared ecological system requiring coordinated international stewardship.

M.Y.S. Prasad (2005)[4] Prasad's work is one of the early Indian scholarly contributions that explicitly links **space debris** with both **technical realities and legal ambiguity**, presenting India/ISRO's evolving position in multilateral discussions. He explains how debris is produced through routine operations (spent rocket stages, mission-related objects, fragmentation) and why "technical uncertainty" (tracking limits, attribution problems, probability-based collision risk) makes legal regulation difficult. A key part of his contribution is the argument that while existing treaties can be *interpreted* to cover debris-related responsibilities, they were not designed with debris-specific measurable standards, so enforcement remains weak. His conclusion is that long-term sustainability requires aligning technical capability (tracking, passivation, disposal) with clearer normative commitments, otherwise law will lag behind the growth of the debris population. **Critical theory lens:** *Regime theory / institutional gap theory*—the paper highlights a mismatch between an older legal regime and new technological realities, producing governance "grey zones."

V. Adimurthy & A.S. Ganeshan (2006)[5] Adimurthy and Ganeshan provide a foundational Indian account of **debris mitigation measures in India**, documenting how ISRO progressively adopted practices aligned with global mitigation norms—particularly steps such as **passivation**, mission planning for safer end-of-life behavior, and the reduction of post-mission fragmentation risks. Their contribution is significant because it frames debris mitigation not as abstract responsibility but as engineering and operational decisions that can be institutionalised inside a national space program. They emphasize that mitigation is achievable through systematic design and mission procedures, but also underline that debris is a global problem: even strong national practice cannot fully prevent risk if other actors do not comply. Their conclusion is that sustained mitigation requires consistent national implementation plus wider international harmonisation. **Critical theory lens:** *Commons governance / collective action theory*—India's mitigation steps are presented as responsible "commons behavior," but overall sustainability depends on coordinated participation of all major actors.

Rajeswari Pillai Rajagopalan (2011)[6] Rajagopalan's analysis, though focused on the broader debate around space codes of conduct, is highly relevant for debris governance because it examines **why global norm-making struggles** when rule-setting appears dominated by a few powers. She argues that governance instruments often face legitimacy deficits if emerging space actors perceive them as non-inclusive, externally designed, or strategically motivated. In the debris context, this matters because effective debris mitigation relies on broad acceptance of shared rules for behavior in orbit. Her conclusion is that a durable space governance framework must be perceived as equitable and participatory—otherwise compliance remains politically contested. **Critical theory lens:** *Constructivism and legitimacy theory*—norms

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work when they are seen as legitimate and co-produced, not imposed; legitimacy becomes a condition for sustainability governance.

Ajey Lele (2016)[7] Lele approaches space governance from the standpoint of **national space security policy**, but his work matters for debris sustainability because it highlights the growing **dual-use nature** of space systems and the policy tensions this creates—especially for transparency, tracking, and operational coordination. He argues that national policy must integrate civil-commercial growth with security planning, which implies stronger institutional capacity for space situational awareness and risk management. His conclusion is that without a coherent national security-space architecture, states may treat orbital governance as strategic competition rather than environmental stewardship, weakening cooperative debris control. **Critical theory lens:** *Realism / security dilemma theory*—space sustainability is constrained when states prioritize strategic advantage; debris governance becomes harder if STM and transparency are framed as security vulnerabilities.

Santosh Kosambe (2019)[8] Kosambe offers a detailed overview of ISRO's debris mitigation activities and highlights concrete technical measures such as **end-of-life passivation** of upper stages and propellant venting systems. The value of this work is its documentation of how mitigation norms translate into mission design and operational protocols. He frames mitigation not as optional ethics but as standard aerospace practice that reduces fragmentation and improves long-term orbital usability. His conclusion is that national programs can build sustainability through "design-for-demise" thinking and systematic end-of-life planning, but effectiveness increases when such standards become consistent across jurisdictions. **Critical theory lens:** *Socio-technical systems theory*—sustainability is produced through the interaction of technology, operational rules, and institutional compliance mechanisms, not by law or engineering alone.

R.K. Sharma (ISRO/Indian Space Debris & SSA research, ~2023–2024)[9] Sharma's work compiles and explains the debris environment and **space situational awareness (SSA)** research efforts associated with ISRO, including fragmentation dynamics, collision risk, catalog growth, and operational conjunction assessment. It is important for sustainability governance because it shows that modern debris management depends on *data capability*: tracking, prediction, warning dissemination, and maneuver decision-support. His conclusion is that debris governance cannot be meaningful without robust SSA infrastructure; sustainability requires routine conjunction assessment, better coordination protocols, and institutional mechanisms that integrate technical risk into governance. **Critical theory lens:** *Risk society / precautionary governance*—when harms are probabilistic and systemic, governance must be preventive and data-driven, not reactive after damage occurs.

Research Questions

1. What legal obligations already exist under international space law that are relevant to debris and sustainability?
2. Why is the present regime insufficient for contemporary debris dynamics and environmental risk?
3. Which governance models can credibly stabilize the orbital environment while preserving innovation and equitable access?

2. The Contemporary Debris Challenge as an Environmental Sustainability Issue

Space debris today presents an environmental risk profile closely comparable to other global commons challenges such as marine plastic pollution and atmospheric climate change. Its impacts are cumulative, as debris objects persist in orbit for decades; transboundary, because orbital paths cross national jurisdictions; difficult to reverse, since debris removal is technically complex and costly; and externally imposed, as the actions of one operator can increase collision risks for all others. *The European Space Agency's* **Space Environment Report 2023** *states that the number of objects in Earth orbit—particularly in* **Low Earth Orbit (LEO)—**

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continues to increase, and that the growth rate of space debris currently exceeds the rate at which natural atmospheric decay can remove it, posing a serious risk to the long-term sustainability of space operations [10].The report highlights that even if all launches were halted immediately, existing debris levels would still be sufficient to generate new debris through collisions, demonstrating that the problem has moved beyond prevention alone and into the realm of long-term environmental management.

From a sustainability perspective, contemporary debris governance must address multiple interconnected dimensions. First, maintaining orbital usability is essential to ensure continued access to space for communication, navigation, weather monitoring, disaster management, and scientific research. Second, reducing the creation of new debris has become critical as mega-constellations increase satellite density and interaction probability. Survey-based analyses conducted between 2020 and 2024 show a sharp rise in conjunction alerts and collision-avoidance manoeuvres, placing increasing operational and financial burdens on satellite operators[11]. Third, end-of-life disposal management—including post-mission deorbiting, graveyard orbit placement, and passivation—has emerged as a key sustainability indicator, with international reports noting inconsistent compliance across operators and states. Fourth, safe operational practices, such as conjunction assessment, data sharing, and Space Traffic Management (STM), are now viewed as essential environmental safeguards rather than optional coordination tools.

However, environmental sustainability requires not only technical solutions but also robust governance structures, many of which current international space law provides only in partial or indirect form. Monitoring and transparency are uneven, as tracking capabilities and data-sharing practices vary widely among states. Minimum performance standards for debris mitigation remain largely non-binding, relying on voluntary guidelines rather than enforceable global norms. Accountability mechanisms are weak, particularly for in-orbit damage where fault attribution is difficult, and legal remedies are rarely pursued in practice. A 2023 UN-linked policy survey noted that while most spacefaring nations acknowledge the debris threat, fewer than half have fully operational enforcement mechanisms for debris mitigation within their national licensing frameworks [12]. These governance gaps have led to a significant conceptual shift in international debates. Rather than treating outer space as an unregulated frontier driven by technological progress and market expansion, scholars and policymakers increasingly frame the orbital environment as a managed commons requiring collective stewardship. Reports submitted to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) between 2019 and 2024 emphasize that sustainability cannot be achieved through unilateral action alone, but depends on shared norms, coordinated traffic management, and equitable access rules. This evolving perspective aligns orbital debris governance with broader environmental governance principles, where prevention, precaution, intergenerational equity, and shared responsibility form the foundation of long-term sustainability strategies.

3. Existing International Legal Obligations Relevant to Space Debris

3.1 Outer Space Treaty: Due Regard, Harmful Contamination, and Consultation

Article IX of the Outer Space Treaty establishes foundational obligations that are directly relevant to the problem of space debris, even though the treaty was drafted at a time when debris was not yet recognised as a major environmental concern. The provision requires states to conduct space activities with “due regard” to the interests of other states, to avoid harmful contamination of outer space, and to undertake international consultations when an activity may cause potentially harmful interference. When interpreted in the context of contemporary orbital congestion, these principles can reasonably be extended to cover the creation of space debris and negligent end-of-life practices, particularly where such actions increase collision risks for other satellites and space operations. The obligation of due regard implies a duty of care in mission planning, satellite operation, and disposal, while the concept of harmful contamination can be understood to include the long-term pollution of orbital environments by persistent debris. However, despite its normative importance, Article IX remains limited in practical effectiveness because it does not specify measurable standards such as disposal timelines, acceptable collision probabilities, or debris-generation thresholds. Moreover, its reliance on diplomatic consultation rather than binding enforcement mechanisms means that compliance depends largely on voluntary cooperation and good faith, reducing its deterrent effect in a highly commercialised and competitive space environment.

3.2 Liability Convention: Compensation Regimes with Limited Deterrence in Orbit

The Convention on International Liability for Damage Caused by Space Objects expands upon Article VII of the Outer Space Treaty by establishing liability rules for damage resulting from space activities. It introduces a dual system in which launching states bear absolute liability for damage caused on the surface of the Earth or to aircraft in flight, while liability for damage occurring elsewhere, including in outer space, is based on fault. In theory, this framework could apply to collisions caused by space debris, allowing affected parties to seek compensation for damage to satellites or other space objects. In practice, however, the fault-based standard poses significant challenges in congested orbital environments, where debris objects may be untracked, fragmented, or difficult to attribute to a specific launching state. Additionally, collision events often result from complex interactions involving multiple operators, shared orbital data, and autonomous avoidance decisions, making it extremely difficult to establish legal fault with certainty. The deterrent value of the Liability Convention is further weakened by the fact that claims must be pursued through diplomatic channels between states, rather than directly by private operators, which limits accessibility and discourages routine use of the mechanism. As a result, while the Convention provides an important legal foundation, it has had only a limited impact on preventing debris generation or promoting sustainable behavior in orbit.

3.3 Registration Convention: Identification and Transparency as Governance Infrastructure

The Convention on Registration of Objects Launched into Outer Space plays a crucial role in establishing transparency and accountability in space activities by requiring launching states to maintain national registries of space objects and furnish relevant information to the United Nations Register. This obligation supports the identification of space objects and the attribution of responsibility, both of which are essential for effective space debris governance. Accurate registration data enables tracking agencies and satellite operators to conduct conjunction assessments, coordinate collision-avoidance manoeuvres, and determine potential liability in the event of damage. From an environmental sustainability perspective, registration functions as a foundational governance infrastructure, without which debris mitigation, space traffic management, and accountability mechanisms cannot operate effectively. However, the practical value of the Registration Convention is constrained by several limitations. Registration information is often incomplete, delayed, or insufficiently detailed for modern operational needs, particularly in highly congested orbital regimes. Moreover, while intact space objects can be registered, the vast majority of debris fragments—especially those created through accidental or explosive fragmentation—cannot be individually registered or reliably attributed. As a result, the Convention provides transparency at a structural level but does not fully support real-time operational safety or comprehensive environmental accountability in orbit.

3.4 Soft Law: UN COPUOS Space Debris Mitigation and Long-Term Sustainability Guidelines

Given the general and principle-based nature of treaty law, much of the practical governance of space debris has developed through non-binding international instruments, commonly referred to as “soft law.” Among the most significant are the Space Debris Mitigation

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Guidelines adopted by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in 2007 and later acknowledged by the United Nations General Assembly. These guidelines outline high-level principles aimed at limiting debris generation during normal operations, preventing on-orbit break-ups, and ensuring safe end-of-life disposal. Building on this foundation, the Guidelines for the Long-term Sustainability (LTS) of Outer Space Activities were adopted by COPUOS in 2019, offering a broader framework that integrates debris mitigation with issues such as space traffic safety, international cooperation, information sharing, and scientific research. In parallel, the Inter-Agency Space Debris Coordination Committee (IADC) has developed and periodically revised detailed technical guidelines that reflect best practices across major space agencies worldwide. Together, these instruments have shaped global expectations regarding responsible behavior in space and have strongly influenced national licensing and regulatory regimes. Nevertheless, their effectiveness remains limited by their non-binding character. Compliance depends entirely on voluntary implementation by states through domestic law and authorization processes, resulting in uneven application and regulatory fragmentation. Consequently, while soft law has been instrumental in norm development, it has not yet ensured uniform or enforceable standards necessary for long-term environmental sustainability in orbit.

4. Fragmented Implementation: Domestic Regulation and Emerging Practice

A defining characteristic of contemporary space debris governance is the gradual shift from multilateral treaty-based regulation toward **national and regional regulatory frameworks**, with domestic licensing emerging as a primary enforcement mechanism. In the United States, for example, the Federal Communications Commission (FCC) has developed detailed orbital debris mitigation rules and application guidelines, requiring satellite operators to demonstrate compliance with disposal planning, collision-risk assessment, and post-mission mitigation measures as a condition for authorization [13]. This licensing-based approach has effectively transformed regulatory approval into a compliance tool, allowing national authorities to enforce sustainability norms even in the absence of binding international standards. At the regional level, the European Union has advanced a coordinated approach to **Space Traffic Management (STM)**, emphasizing operational safety, data sharing, and standardized traffic coordination to maintain orbital usability amid increasing congestion. In parallel, plurilateral initiatives such as the **Artemis Accords** have introduced commitments related to orbital debris mitigation and responsible end-of-life disposal, contributing to norm-building outside the traditional United Nations treaty framework. While these developments reflect pragmatic responses to rapidly evolving space activities, they also signal a broader governance shift in which authority is increasingly dispersed across domestic regulations, regional STM initiatives, and selective multilateral arrangements. The resulting patchwork system raises concerns about regulatory fragmentation, inconsistent standards, and unequal compliance burdens—particularly for emerging space actors and smaller operators—thereby challenging the goal of equitable and sustainable management of the orbital environment.

5. Core Gaps in the Current Legal Regime

Non-binding Standards versus Binding Harms

One of the most fundamental weaknesses in the current legal framework governing space debris lies in the mismatch between the **binding nature of the harm** and the **non-binding nature of the regulatory response**. Space debris causes structural and collective damage to the orbital environment, as its effects accumulate over time and affect all space users regardless of who created the debris. However, most existing mitigation norms—such as those developed under COPUOS, the Inter-Agency Space Debris Coordination Committee (IADC), and the Long-Term Sustainability (LTS) Guidelines—remain voluntary in nature. This creates a classic collective action problem in which individual operators bear the private costs of mitigation, such as fuel expenditure, design modifications, and shortened mission lifetimes, while the benefits of a cleaner orbital environment are shared by all users. As a result, incentives for full compliance are weak, leading to under-implementation and uneven adherence across states and operators. Without binding minimum standards, responsible actors may be disadvantaged relative to those who externalize environmental risks, undermining overall sustainability.

Fault and Attribution Problems

Another major gap in the existing legal regime concerns the difficulty of establishing **fault and attribution** for debris-related damage in orbit. Although the Liability Convention provides a legal basis for compensation, its fault-based liability standard for damage occurring in outer space poses serious practical challenges. In congested orbital environments, debris objects are often small, untracked, or fragmented, making it difficult to identify their origin with certainty. Even when attribution is technically possible, collision events frequently involve multiple contributing factors, such as shared tracking data, autonomous manoeuvre decisions, and probabilistic risk assessments, complicating the legal determination of fault. The absence of clear fault attribution significantly weakens the deterrent effect of liability rules, as operators may not expect to face legal consequences for debris-related incidents. Consequently, liability law has played only a limited role in influencing operational behavior or preventing debris generation.

Absence of a Dedicated International Space Traffic Management Authority

Despite the growing recognition that **traffic coordination is essential** in an increasingly congested orbital environment, international space law lacks a dedicated institutional framework for Space Traffic Management (STM). No global authority currently exists with the mandate to set binding STM rules, standardize conjunction assessment protocols, or coordinate enforcement across jurisdictions. While individual states and regional bodies have begun developing their own STM practices, these efforts remain fragmented and lack universal applicability. The absence of a centralized or coordinated STM mechanism increases the risk of inconsistent data standards, delayed warnings, and conflicting manoeuvre decisions, all of which heighten collision risk. This institutional vacuum represents a critical governance gap, as effective debris mitigation increasingly depends on real-time coordination, shared situational awareness, and agreed "rules of the road" for orbital operations.

Equity and Access Concerns

Any effort to strengthen space debris regulation must also address issues of **equity and access**, particularly for emerging spacefaring nations and smaller commercial operators. Stricter mitigation requirements—such as advanced tracking capabilities, enhanced disposal systems, or financial bonding mechanisms—can impose significant costs that may disproportionately burden actors with limited technical and financial resources. Without appropriate capacity-building measures and differentiated responsibilities, more stringent regimes risk reinforcing existing inequalities in access to outer space. This concern is especially important in light of the cooperative spirit of the Outer Space Treaty, which emphasizes that outer space should be explored and used for the benefit of all countries. A sustainable governance framework must therefore balance environmental protection with inclusiveness, ensuring that new entrants are supported rather than excluded from responsible participation in space activities.

6. Future Governance Models for Sustainable Orbits

Model A: "Hardened Soft Law" through Licensing Harmonization (Near-term and Realistic)

One of the most practical and immediately achievable governance pathways for addressing space debris is the strengthening of existing soft-law norms through national licensing systems. Rather than renegotiating international treaties, this model proposes converting internationally accepted guidelines—such as those developed under COPUOS, the Inter-Agency Space Debris Coordination Committee (IADC), and the Long-Term Sustainability (LTS) framework—into enforceable minimum standards applied through domestic authorization and supervision.

States would require compliance with these norms as a condition for granting licenses for launches, satellite communications, and in-orbit operations. Regulatory authorities could gradually converge on measurable performance indicators, including post-mission disposal deadlines, passivation requirements, prevention of mission-related debris release, acceptable collision-risk thresholds, and credible end-of-life disposal plans. The use of technical standards, such as ISO debris mitigation requirements, would further enhance uniformity, transparency, and auditability. The primary strength of this model lies in its feasibility, as it builds on existing regulatory practice and leverages market access as a compliance incentive. However, its effectiveness may be limited by uneven adoption across jurisdictions, the risk of regulatory arbitrage by operators seeking less stringent licensing regimes, and weak international coordination.

Model B: International Space Traffic Management Coordination Compact (Mid-term)

A second governance model focuses on the development of an international Space Traffic Management (STM) coordination compact aimed at reducing collision risk in increasingly congested orbits. This model envisions a multilateral framework agreement that standardizes key operational elements, including conjunction data-sharing protocols, notification and manoeuvre coordination rules, minimum tracking accuracy and ephemeris quality standards, and transparent incident reporting procedures. Rather than creating an entirely new institution from the outset, regional initiatives—such as the European Union's emerging STM approach—could serve as building blocks for wider international harmonization. The United Nations system, particularly through COPUOS, could provide legitimacy, inclusiveness, and a neutral forum for coordination. The principal advantage of this model is that it directly addresses the operational causes of collisions by improving predictability, coordination, and trust among space actors. Nonetheless, significant challenges remain, including national security sensitivities surrounding data sharing, classification of tracking information, and disparities in technical and institutional capacity between established and emerging spacefaring nations.

Model C: Orbital Environmental Impact Assessment (OEIA) as a Global Norm (Mid-term)

A more explicitly environmental governance approach involves the introduction of Orbital Environmental Impact Assessments (OEIAs) as a global norm for space activities with significant debris risk. Under this model, large satellite constellations and high-risk missions would be treated as environmentally significant activities requiring prior assessment before authorization, drawing a parallel with environmental impact assessment practices on Earth. An OEIA would evaluate factors such as projected debris generation, reliability of end-of-life disposal, expected conjunction burden on existing operators, and cumulative impacts on orbital regions. This approach is conceptually grounded in Article IX of the Outer Space Treaty, particularly the obligation to avoid "potentially harmful interference" and to consult internationally where such risks arise. The strength of the OEIA model lies in its alignment with environmental sustainability principles, including precaution, prevention, and cumulative risk management. However, its implementation could face resistance due to disagreements over assessment standards, scope, and thresholds, and there is a risk that poorly designed procedures could become bureaucratic obstacles unless carefully streamlined.

Model D: Economic Instruments—Orbital-use Fees, Bonding, and Insurance (Incentive-Compatible Governance)

An alternative governance strategy focuses on economic instruments designed to internalize the external costs of orbital congestion and debris creation. This model proposes the introduction of orbital-use fees calibrated according to factors such as altitude, orbital lifetime, satellite mass, and collision risk, thereby reflecting the environmental burden imposed by different missions. Complementary mechanisms could include end-of-life financial bonds that are refunded upon verified disposal and insurance requirements scaled to debris-related risk profiles. By attaching a price signal to orbital use, this approach directly addresses the free-rider problem that undermines voluntary compliance, encouraging operators to design satellites for safer disposal and shorter orbital persistence. The principal strength of this model is its incentive compatibility, as it aligns private decision-making with collective environmental outcomes. However, its effectiveness depends on reliable monitoring and verification systems, and it raises equity concerns if financial costs disproportionately restrict access for emerging space nations or smaller commercial actors.

Model E: Treaty Protocol on Space Debris and Remediation (Long-term and High Ambition)

The most comprehensive, though politically challenging, governance option involves the adoption of a binding international protocol specifically addressing space debris and orbital remediation. Such a protocol, whether developed under the Outer Space Treaty framework or as a standalone treaty, would codify minimum requirements for disposal and passivation, establish shared rules for active debris removal (ADR) and remediation activities, clarify the legal status of debris capture with respect to consent and salvage limitations, and strengthen liability presumptions in cases of negligent non-disposal. This model builds upon existing treaty principles—such as due regard, state responsibility, and liability—but translates them into concrete, measurable obligations capable of supporting enforcement and verification. Its principal advantage is the creation of a globally uniform baseline that could significantly reduce fragmentation and regulatory inconsistency. However, the model faces substantial risks, including slow negotiation processes, geopolitical deadlock, and complex challenges related to compliance monitoring and verification in a contested strategic environment.

7. A Hybrid Governance Architecture: Recommended Pathway

In light of current political constraints, technological disparities, and the urgent need for effective action, this paper recommends a **hybrid governance architecture** that combines enforceable national regulation with coordinated international oversight. At its core, this approach establishes a binding baseline through national licensing systems by embedding widely accepted soft-law principles—such as those developed under COPUOS, the Long-Term Sustainability (LTS) Guidelines, and the Inter-Agency Space Debris Coordination Committee (IADC)—as mandatory conditions for authorization and supervision. This ensures immediate enforceability without requiring treaty renegotiation. Complementing this baseline, an international Space Traffic Management (STM) coordination compact would provide shared operational rules, standardized data protocols, and agreed "rules of the road," building incrementally on existing regional STM initiatives to enhance predictability and collision avoidance. To address the economic drivers of debris creation, the framework incorporates incentive-based instruments such as orbital-use fees, end-of-life bonding mechanisms, and risk-based insurance requirements, thereby internalizing congestion costs and generating resources for debris remediation and capacity-building. Finally, the architecture is anchored in a legitimacy and equity layer facilitated through the United Nations system, particularly the COPUOS forum, to ensure inclusiveness, transparency, and differentiated support for emerging space actors. Taken together, this hybrid model treats orbital space as a protected environmental commons while remaining institutionally pragmatic by leveraging national licensing for enforcement and multilateral cooperation for coordination and fairness.

8. Conclusion

Space debris governance is at a transition point: the orbital environment has become dense enough that voluntary mitigation, while necessary, is insufficient. Existing international space law provides foundational principles—due regard, contamination avoidance, consultation, registration, and liability—but does not supply measurable standards or enforcement suitable for modern mega-constellation dynamics. Current governance therefore relies on domestic regulation and soft-law norms, producing fragmentation risks.

ISSN: 2393-8048
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SJIF Impact Factor =8.152, January-June 2025, Submitted in February 2025

A sustainable future requires governance that is measurable, enforceable, coordinated, and equitable. The most viable route is a hybrid framework—hardening soft law through licensing, establishing STM coordination rules, embedding incentive-compatible economics, and anchoring legitimacy in inclusive multilateral processes. This approach can stabilize the orbital environment while preserving the benefits of space systems for present and future generations.

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