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Space Debris and Its Environmental Implications: Legal Challenges and The Need for Futuristic Space Laws

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ABSTRACT
Debris on atmospheric re-entry makes the space junk environment dangerous for ground-based infrastructure and spacecraft systems. Having six satellites in geostationary and low Earth orbit, Indonesia has been exploring space since the 1960s. From environmental to legal, modern space exploration faces difficult obstacles related to space junk. Low Earth Orbit (LEO) and geostationary satellites contain most of the space junk. Commercial launch activities and space traffic congestion increase the risk of satellite accidents and space junk chains producing Kessler Syndrome. The lack of effective garbage mitigating strategies will make LEO and GEO rather dangerous places that must be addressed by quick legislative and technical solutions for space sustainability. Under satellite monitoring, the European Space Agency detects more than 30,000 pieces of space junk with millions of particles smaller than 1 cm and around 200,000 between 1 and 10 cm. new rules beyond present governance methods provide regulatory challenges that affect the rising number of commercial space exploration missions. Proposed by NASA engineer Donald J. Kessler in 1978, the Kessler Syndrome suggests that increased debris resulting from collisions among satellites causes more debris, hence increasing the likelihood of future strikes. Without appropriate space traffic management, debris lowering technologies, and strong international treaties, space trash environmental hazards might permanently harm the Earth's orbital space.

Keywords: Space debris, Environmental impact, Kessler's effect, International Law and Treaties

1. INTRODUCTION

A substantial accumulation of defunct satellites and space garbage has resulted from expended rocket stages, retired spacecraft, and more orbital detritus. The space debris environment presents two categories of safety concerns: it endangers spacecraft systems in Earth orbit and causes risks to terrestrial infrastructure due to surviving debris during atmospheric re-entry. Indonesia promptly initiated space efforts in the early 1960s (Montrose Environmental Group, 2025)[1]. Since 1970, Indonesia has initiated rocket development, which culminated in the establishment of space science and technology projects by 1980. Currently, the nation runs six satellites positioned in geostationary orbit and low Earth orbit.

[1] Montrose Environmental Group. (2025, January 31). New Horizons: Brownfields Restoration [Webinar]. Retrieved from https://www.montrose-env.com

Contemporary space exploration has two significant challenges with space debris, both from an environmental and a legal viewpoint. The proliferation of launched satellites, decommissioned spacecraft, and fragmenting collisions is generating a growing congestion in Earth's orbital zones, jeopardising existing satellite operations and future space initiatives. International standards for space debris mitigation and responsibility frameworks are inadequate, resulting in significant legal difficulties (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, 1967)[2]. Futuristic space legislation is essential for the expansion of space activities, as it aims to safeguard sustainable practices, mitigate space pollution, and create responsibility requirements. The study examines the impact of space debris on the environment and the necessary legal reforms to implement appropriate policies for space sustainability.

1.1. BACKGROUND

Figure 1 Image of Space debris over the periods

- **Definition and Overview of Space Debris**

Space debris refers to any objects that mankind no longer utilises or has abandoned in outer space. This includes paint fragments, obsolete rocket parts, remnants from prior incidents, and impaired satellites. The proliferation of space exploration has exacerbated the problem of orbital debris (Byers & Boley, 2023).[3] Certain space debris persists in Earth's orbit for prolonged durations, presenting a hazard to functional satellites and space missions. The predominant composition of space debris consists of elements used in rocket launches and defunct satellites. The preponderance of space debris resides in Low Earth Orbit (LEO), situated at an altitude of fewer than 2,000 miles above the Earth's surface. Certain satellites are positioned in geostationary orbit at an altitude of 35,786 miles above the equator (Jasentuliyana, 2023)[4].

[2] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moonand Other Celestial Bodies; 610 UNTS 205; entered into force on 10 October 1967.27.

[3] Byers, M., & Boley, A. (2023). Who owns Outer Space?: International law, astrophysics, and the sustainable development of space (Vol. 176). Cambridge University Press.

[4] Jasentuliyana, N. (2023). International space law and the United Nations. Brill.

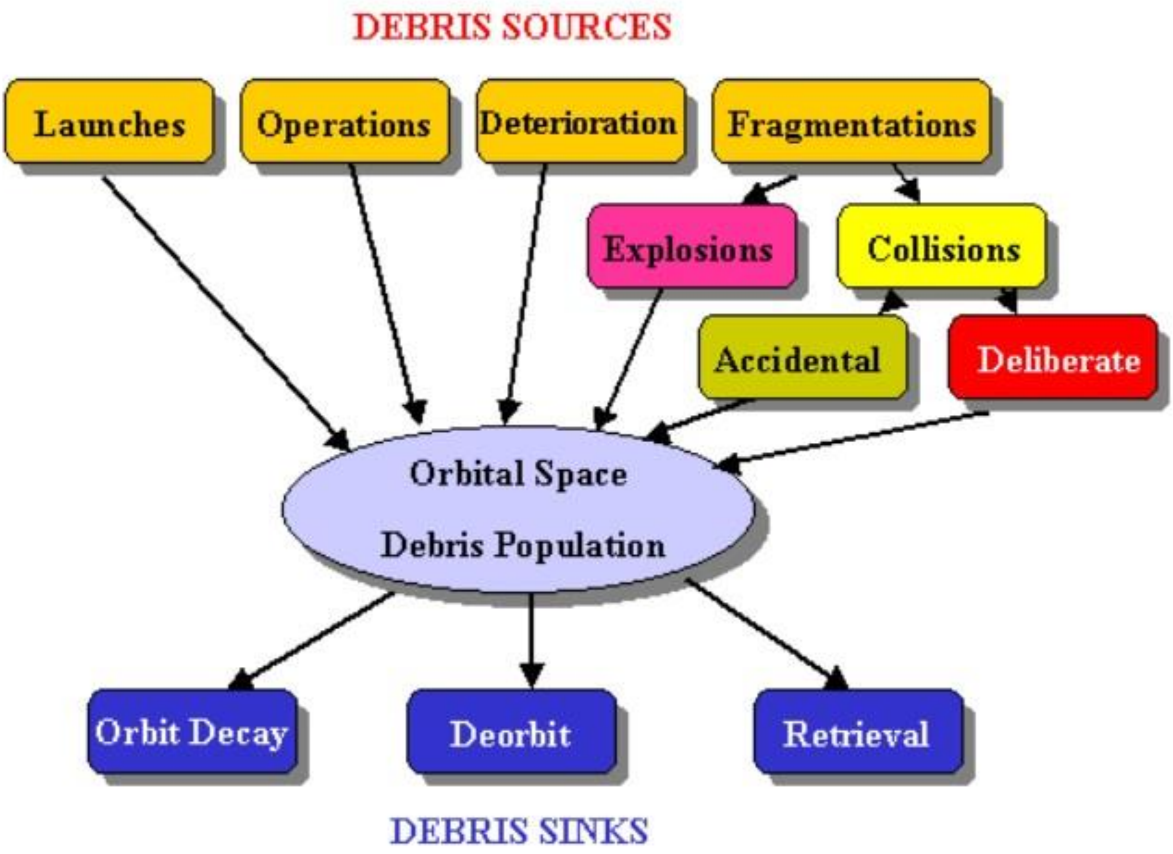

Figure 2 Debris Sinks and Sources

This consists of various objects ranging from the minute paint chip to substantial inert satellites that can move at the speed of some hundreds of km/s to be a threat towards operational satellites, space missions together with astronauts. Space traffic density and commercial launches now accelerate the risk of satellite crashes and following space debris chains that lead to Kessler Syndrome (Masson-Zwaan & Hofmann, 2024)[5]. The lack of effective debris mitigation strategies will turn LEO and GEO into highly dangerous regions that require immediate legal and technological solutions for space sustainability.

Space Debris: Origin, Types, and Current Scenario

The collection of space debris occurs mainly from failed satellites along with spent rocket stages and the remnants created by satellite collisions and operational orbital materials. Space debris exists because of defective satellites together with uncontrolled spacecraft re-entries and anti-satellite testing events and unplanned spacecraft fragmentations.

Big debris and small debris represent the main classifications among space orbital objects.

Big debris refers to dead satellites alongside rocket bodies making up the greatest collision danger (Oche, Ewa, & Ibekwe, 2021)[6].

High-speed paint chips and explosion fragments created through human activities comprise small debris that inflicts severe damage. Orbital congestion becomes worse due to both categories of debris and this makes collisions more probable as well as increases the risk of Kessler Syndrome and enduring space pollution.

[5] Masson-Zwaan, T., & Hofmann, M. (2024). Introduction to space law. Kluwer Law International BV..

[6] Oche, P. A., Ewa, G. A., & Ibekwe, N. (2021). Applications and challenges of artificial intelligence in space missions. IEEE Access, 12, 44481-44509.

Current Situation with Space Junk

The European Space Agency's Satellite Environment Report 2022 states that there are over 30,000 pieces of space debris that are constantly being tracked by satellite networks.

Tiny Debris: Millions of particles are less than 1 cm in size, while around 200,000 are between 1 and 10 cm (Falco & Boschetti, 2021).[7]

Roughly 34,000 of these things are larger than 10 cm.

In 2022, there were around 6,718 operational satellites in Earth's orbit, which amounted to an increase of more than 2,000 spacecraft, demonstrating the growing number of satellite constellations.

- **Importance of Space Sustainability**

Space sustainability is often inadequately executed, with a clear correlation between space and terrestrial sustainability. Current laws and corrective efforts are insufficient to ensure long-term viability. The proliferation of commercial space enterprises has exacerbated orbital congestion due to space debris spread and increased space transportation. The environmental impact of the sector is increasing, potentially making it untenable to use space to advance the Sustainable Development Goals (SDGs) (Shittu, Williams, & Shaw, 2021)[8]. The "space sustainability paradox" highlights this discrepancy. Contemporary space policy must address the increasing challenges of orbital debris and space traffic management, with stringent restrictions and penalties for noncompliance. The International Association for the Advancement of Space Safety (IAASS) suggests proper spacecraft disposal and preventing in-orbit explosions as methods to mitigate space debris. The ClearSpace-1 mission and similar programs demonstrate the growing space debris remediation industry. Countries and groups in space exploration must collaborate to provide a sustainable framework for future space endeavours, enhancing controls and global collaboration to mitigate the adverse effects of space resources on Earth's ecosystems and ensure the seamless execution of space missions (Pardini & Anselmo, 2021)[9].

2. LITERATURE REVIEWS

Environmental Implications of Space Debris

According to (Andriansyah, Sulastri, & Satispi, 2021) [10]Since the start of the space age in 1957, there has been no clear plan for the deactivation of numerous rockets, spacecraft, and satellites in orbit. The European Space Agency (ESA) reports that there are an estimated 900,000 inoperable objects larger than one millimetre in Earth's orbit, endangering future space missions and terrestrial communications. Space debris, including defunct satellites, rocket parts, and collision fragments, poses a serious hazard to terrestrial telecommunications and operational missions (Brownlie, 2003)[11]. The UN Office for Outer Space Affairs (UNOOSA) has long stressed the need for preventative actions to reduce the risks posed by space debris. The majority of the approximately 560 fragmentation accidents since 1961 may be attributed

[7] Falco, G., & Boschetti, N. (2021). A security risk taxonomy for commercial space missions. In *ASCEND 2021* (p. 4241).

[8] Shittu, O. S., Williams, I. D., & Shaw, P. J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Management, 120, 549-563.

[9] Pardini, C., & Anselmo, L. (2021). Evaluating the impact of space activities in low earth orbit. *Acta Astronautica*, *184*, 11-22

[10] Andriansyah, A., Sulastri, E., & Satispi, E. (2021). The role of government policies in environmental management. Research Horizon, 1(3), 86-93

[11] Brownlie, I. Principles of Public International Law, 6th ed.; Diakonia: Bromma, Sweden, 2003; pp. 6–12. ISBN978-0199260713.34. Jakhu, R. Legal issues relating to the global public interest in outer space. J. Space Law 2006,32, 31–110.35.

to fuel explosions in rocket stages. Small debris, such as micrometeorites and solid fuel residues, may damage solar panels on functioning spacecraft. Upon return to Earth, several Russian spacecraft may pose a danger of radioactive contamination due to their nuclear batteries (Hobe, 2007)[12]. Discarded objects in low Earth orbit pose a serious threat to future space exploration, with garbage volume increasing by 1.5 times in the next 200 years. NASA has had a plan and guidelines in place to reduce trash in orbit since the 1990s.

Existing Legal Framework for Space Debris

Space operations are governed by a system of laws, including space laws enacted by over twenty nations, resolutions issued by the United Nations General Assembly, and five international treaties (UNOOSA, 2018)[13]. The Outer Space Treaty (OST) recognizes space and celestial bodies as a universal common, ensuring unfettered access to space exploration and usage. Article I of the OST guarantees freedom to study the cosmos and its objects, but there is no total or endless spatial freedom.

The stewardship of space is based on a sense of duty to other generations, with every nation and generation having an inherent right to explore and use space and celestial bodies. The Common Heritage of Mankind (CHM) idea aims to protect and ensure the continued integrity of globally important regions for future generations (Brownlie, 2003)[14]. Article IX of the OST forbids the use of space for military objectives and guarantees environmental protection, emphasizing the responsibility of nations in engaging in space operations.

There is no clear prohibition against the production of space garbage or the removal of space objects from orbit. Many nations' legal systems have begun to embrace mitigation strategies, while others have adopted them as optional, non-binding standards (Montrose Environmental Group, 2025)[15]. There is no mandated way to sustainability under existing space legislation.

2.1. RESEARCH GAP

The Outer Space Treaty of 1967 and Liability Convention of 1972 [16]fail to deliver an effective system for spaces debris management because they lack sufficient capability in this area. The growing number of commercial space exploration activities faces regulatory challenges because new rules exceed established governance methods. The paper demonstrates that the regulatory system lacks binding international agreements and effective enforcement methods thus requiring new global governance structures and environment-friendly cleaning solutions and policy innovations for space operation control.

2.2. RESEARCH QUESTION

1. I What are the origins and forms of space debris, and how do they impact the modern orbital environment surrounding Earth?
2. II How do space junk environmental issues, such as the Kessler Syndrome, pose a threat to orbital sustainability?

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[12] Hobe, S. Outer Space as the Province of All Mankind—An Assessment of 40 years of Development.

[13] United Nations Office for Outer Space Affairs. Space Law Treaties and Principles. Available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties.html
en.wikipedia.org

[14] Brownlie, I. Principles of Public International Law, 6th ed.; Diakonia: Bromma, Sweden, 2003; pp. 6–12. ISBN978-0199260713.34. Jakhu, R. Legal issues relating to the global public interest in outer space. J. Space Law 2006,32, 31–110.35.

[15] Montrose Environmental Group. (2025, January 31). **New Horizons: Brownfields Restoration** [Webinar]. Retrieved from *https://www.montrose-env.com*

[16] Convention on International Liability for Damage Caused by Space Objects. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html

3. III What are the existing international rules and recommendations addressing responsibilities for space debris control?
4. **IV** What functional laws and operational approaches can be proposed to ensure the sustainability of outer space?

2.3. IMPORTANCE OF THE STUDY

Growing space debris now creates dangerous operational challenges for satellite communications systems and space exploration since it threatens the orbital stability of Earth. New space exploration initiatives launched jointly by governments and commercial companies continue to create orbital space pollutants that escalate the risk for spacecraft collisions. Legal frameworks constitute essential instruments to control space waste management procedures alongside defining responsibility for sustainable outer space governance. International space legislation needs reform to jointly advance technology with policy structures which will control uncontrolled growth of space debris thereby maintaining outer space longevity for scientific and defensive pursuits.

2.4. RESEARCH OBJECTIVES

1. To evaluate the origins and forms as well as their modern effects on the orbital environment encircling Earth.
2. To investigate space junk environmental issues endangering orbital sustainability via Kessler Syndrome.
3. To analyse present international rules as well as recommendations addressing duties for space debris control.
4. To suggest the creation of functional laws and operational approaches to ensure outer space sustainability.

3. RESEARCH METHODOLOGY

This chapter presents a research methodology for a critical analysis of the relationship between space law, satellite constellation-based internet, and its impact on cyber security. A mixed-method research design is used, combining quantitative and qualitative approaches. Data collection methods include surveys, interviews, and purposive sampling. Surveys assess the current state of space law and satellite mega-constellations, while in-depth interviews with key stakeholders provide qualitative insights. Purposive sampling selects experts with extensive knowledge in these domains. Quantitative data collected through surveys is analyzed using statistical tools to identify trends and correlations. Thematic analysis identifies common themes and patterns related to space law, satellite technology, and cyber security, providing a qualitative context for the study.

3.1. RESEARCH METHOD & DESIGN

This study uses a mixed-method research approach, combining both quantitative and qualitative methodologies to thoroughly examine the connection between space law, satellite constellation-based internet, and cybersecurity. The quantitative part involves surveys to evaluate legal frameworks, technological advancements, and cyber risks in satellite networks. Meanwhile, the qualitative component includes in-depth interviews with key stakeholders, such as legal professionals, technology experts, and policymakers, to gain deeper insights. This research design incorporates triangulation to enhance validity and reliability. Data will be systematically gathered using purposive sampling and analyzed through statistical tools for numerical patterns and thematic analysis for qualitative findings.

3.2. RESEARCH APPROACH

This study adopts a mixed-method research approach, integrating both quantitative and qualitative methodologies to provide a comprehensive analysis of the relationship between space law, satellite constellation-based internet, and cybersecurity.

Quantitative Approach: Surveys will be conducted to assess legal frameworks, technological advancements, and cybersecurity threats in satellite networks. This numerical data will be analyzed using statistical tools to identify trends and patterns.

Qualitative Approach: In-depth interviews with legal experts, technology specialists, and policymakers will be conducted to gather nuanced insights. The qualitative data will be analyzed using thematic analysis to identify key themes and perspectives.

By employing triangulation, this research approach enhances the validity and reliability of the findings. Data collection will follow a systematic process, using purposive sampling to ensure relevance and depth in both quantitative and qualitative analyses.

4. ANALYSIS OF STUDY

4.1 INTRODUCTION TO THE ANALYSIS CHAPTER

Satellite technology and space exploration have revolutionized defense, navigation, scientific investigation, and communication, but they have also led to the creation of space junk, or "space trash (Deplano, 2021)[17]." This waste, consisting of destroyed satellites, rocket fragments, and abandoned equipment, poses a significant threat to Earth's sustainability and increases the risk of catastrophic accidents. The increasing concentration of space junk in low Earth orbit and geostationary orbit poses a hazard to collisions that could damage GPS, global communications, and weather forecasting services. The Kessler Syndrome, a cascading chain reaction of collisions due to the accumulation of trash, is a key issue in orbital sustainability. Geopolitical conflicts from military satellites, anti-satellite weapons tests, and space-based monitoring constellations complicate space junk control (Andriansyah, Sulastri, & Satispi, 2021)[18]. Private players like SpaceX have added new dimensions to worldwide collaboration and questions about responsibility and regulation in the commercial sector. Previous international rules and recommendations for space debris control cover structures such as the Outer Space Treaty (1967)[19], Liability Convention (1972)[20], and rules of organizations like the United Nations Office for Outer Space Affairs (UNOOSA) and Inter-Agency Space Debris Coordinating Committee (IADC). New and legally enforceable international laws are needed as technical advancements outpace control development.

[17] Deplano, R. (2021). The Artemis Accords: Evolution or revolution in international space law?. International & Comparative Law Quarterly, 70(3), 799-819

[18] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

[19] Convention on International Liability for Damage Caused by Space Objects https://www.faa.gov/about/office_org/headquarters_offices/ast/media/Conv_International_Liab_Damage.pdf

[20] Space Liability Convention of 1972 https://iasbaba.com/2022/08/space-liability-convention-of-1972/

4.2. ORIGINS AND FORMS OF SPACE DEBRIS: IMPACTS ON EARTH'S ORBITAL ENVIRONMENT

Dead satellites, abandoned launch vehicle stages, bits of broken spacecraft, and other space mission remnants make up space rubbish, or space debris (Pardini & Anselmo, 2021)[21]. From the start of the space era when Sputnik 1 was launched in 1957, humans have progressively crowded Earth's orbital space with both useful spacecraft and trash. Although technological developments have greatly improved communication, navigation, and scientific discoveries as well as other areas, the proliferation of space junk seriously jeopardizes operating satellites, human spaceflight, and long-term viability of outer space activities. The origins and forms of space junk as well as their influence on the orbit of Earth in this part.

Origins of Space Debris

1. Fragments Events

Fragments of satellites and rockets are one of the main causes of the trash population. Usually arising from leftover fuel or battery failures on spacecraft and upper-stage rockets, fragmentation occurrences result from explosions. About forty percent of the recorded garbage is accidental break-through; one event produces hundreds of tiny fragments (Shittu, Williams, & Shaw, 2021)[22]. China's anti-satellite (ASAT) test in 2007, for example, blew up one of their defunct spacecrafts, producing more than 3,000 trackable bits of garbage some of which still circle the earth today. In a similar vein, the 2009 collision between the functional Iridium 33 communications satellite and the defunct Russian spacecraft Cosmos 2251 sent about 2,000 bits of garbage into Earth's orbit. These kinds of incidents highlight how both deliberate and accidental accidents greatly increase the count of trash items.

2. Rocket Stages and Dead Spacecraft

Once their mission is over, faulty spacecraft and spent rocket stages left in orbit constitute the other significant cause of trash (Falco & Boschetti, 2021)[23]. Most of the time, satellites run out of their useful lifetime without any intention of deorbit, therefore rendering themselves drifting idly. Especially the earlier models, launch rockets sometimes lose top stages in orbit, resulting in large inactive objects with possible collision capability. With time, these things deteriorate and produce additional trash. The likelihood of accidental collisions rises with thousands of rocket stages and more than 3,000 dead satellites orbiting Earth.

3. Operational Debris and Object Related to Missions

Furthermore, contributing to the accumulation of trash are regular space missions. Some instances are:

- Abanded tools during extravehicular activities (EVAs), memorably seen when an astronaut lost a toolbox on a spacewalk in 2008;
- Jettisoned separation bolts and lens covers (Oche, Ewa, & Ibekwe, 2021).[24]
- Fragments released from crumbling insulating materials or during fuel venting procedures.

Given their great speeds, these little but significant quantities of items are very harmful. For satellites flying at 7-8 km/s, even 1 cm-sized trash may be catastrophic.

[21] Pardini, C., & Anselmo, L. (2021). Evaluating the impact of space activities in low earth orbit. Acta Astronautica, 184, 11-22.

[22] Shittu, O. S., Williams, I. D., & Shaw, P. J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Management, 120, 549-563

[23] Falco, G., & Boschetti, N. (2021). A security risk taxonomy for commercial space missions. In ASCEND 2021 (p. 4241)

[24] Oche, P. A., Ewa, G. A., & Ibekwe, N. (2021). Applications and challenges of artificial intelligence in space missions. IEEE Access, 12, 44481-44509

4. Active Debris-Creation Activities

Certain military activities include missile interceptions and anti-satellite testing (ASAT) have been intentionally producing space junk. Countries like the United States of America, Russia, China, and India have conducted such experiments, generating global concerns about environmental effects and weaponizing of outer space. While some of them re-enter Earth's atmosphere after a few months, others persist for decades and provide long-term hazards.

Forms of Space Debris

Size, form, and substance vary widely in space junk. Significant collision hazards come from large trash containing mission-related items and dead satellites and equipment (Masson-Zwaan & Hofmann, 2024)[25]. Because of its destructive power and tracking challenges, medium-sized trash—between 1 cm and 10 cm—is hazardous. Smaller than 1 cm, micro-debris are difficult to find yet over time they may degrade spacecraft surfaces. An estimated 900,000 items between 1-10 cm and millions of micro-debris remain unnoticed while the U.S. Space Surveillance Network monitors approximately 30,000 objects bigger than 10 cm. Particularly in the low Earth orbit area, where satellites and the International Space Station operate, this results in highly crowded surroundings.

Impacts on Earth's Orbital Environment

Rising Debris Density Threatens Spaceflight and Human Spaceflight

- Debris density poses a threat to satellites and spacecraft, affecting vital services like GPS, telephony, weather monitoring, and military systems.
- The International Space Station (ISS) starts 29 maneuvering operations to avoid collisions, reducing the operating life of spacecraft.
- The Kessler Syndrome, a potential scenario where collisions produce extra impacts, threatens human spaceflight (Jasentuliyana, 2023).[26]
- The financial expenses of debris-related satellite losses are estimated in billions of dollars annually.
- Environmental issues exist beyond space, with large amounts of trash entering Earth's atmosphere potentially causing ground damage.
- Rising insurance rates, legal obstacles, and operational challenges threaten the long-term survival of outer space activities.
- Private companies like SpaceX present new challenges for traffic control and debris avoidance, necessitating international collaboration.
- Technological developments, operational methods, and geopolitics interact to produce the spread of space junk (Byers & Boley, 2023).[27]
- Proactive mitigating strategies are essential to ensure safe and sustainable access to outer space.

4.3. ENVIRONMENTAL THREATS OF SPACE JUNK: THE ROLE OF KESSLER SYNDROME IN ORBITAL SUSTAINABILITY

Modern life relies heavily on space technology for communication, navigation, military, meteorology, and scientific discovery. However, the increasing number of satellites and space missions has led to a significant buildup of space junk, posing a major environmental threat to Earth's orbital sustainability

[25] Masson-Zwaan, T., & Hofmann, M. (2024). Introduction to space law. Kluwer Law International BV.
[26] Jasentuliyana, N. (2023). International space law and the United Nations. Brill.
[27] Byers, M., & Boley, A. (2023). Who owns Outer Space?: International law, astrophysics, and the sustainable development of space (Vol. 176). Cambridge University Press

(Miraux, 2022)[28]. The Kessler Syndrome, developed in 1978 by NASA engineer Donald J. Kessler, suggests that increasing debris from collisions between bodies creates more debris, increasing the risk of future impacts. Unchecked, this chain could make vast areas of orbit unreachable for decades. This article discusses the geopolitical aspects of orbital clutter, the environmental consequences of space junk, contributions from commercial companies like SpaceX, and the dangers of militarization and conflict in space.

Understanding the Kessler Syndrome

Under Kessler Syndrome, the concentration of objects in Earth's orbit reaches a tipping point when collisions between satellites produce additional debris, therefore increasing the probability of future collisions (Martin & Freeland, 2021)[29]. Operating satellites, spacecraft, and human missions all at risk when trash breaks apart. At 7-8 km/s, even little bits may be rather destructive.

With most of the world's communication, Earth observation satellites, and the International Space Station (ISS) located in the Low Earth Orbit (LEO), which covers 200 km to 2,000km above the surface of Earth, the Kessler Syndrome poses the greatest danger there. Congestion also progressively threatens the Geostationary Orbit (GEO), which is necessary for meteorological satellites and telecommunications.

Environmental Threats Posed by Space Junk

Space debris poses significant risks to satellites, disrupting military intelligence, GPS, weather monitoring, and communication networks (Palmroth et al., 2021).[30] The International Space Station (ISS) has implemented several evasive manoeuvres to avoid debris, ensuring astronaut safety. Space junk also incurs significant financial costs, with damage, insurance, and mitigating costs amounting to billions of dollars annually. Accidents can disrupt sectors like military, banking, aviation, and agriculture. Environmentally, falling satellite garbage may re-enter Earth's atmosphere, posing significant threats to populated areas. Uncontrolled debris falls like China's Long March 5B in 2021 highlight global safety concerns. Future astronautical discovery may be affected by trash accumulation, limiting access to valuable orbital slots and delaying technological advancement (Wolfrum, 1983).[31] As debris accumulates, some orbits may be closed for further flights, posing navigation issues for Mars, moon, and scientific missions.

Geopolitical Dimensions of Space Junk

Space has become a global strategic area, with major space-farers like the United States, Russia, China, India, and the European Union vying for orbital domination. The growing military and dual-use satellite deployment raises questions about space militarization, as anti-satellite missiles create debris and worsen the Kessler Syndrome danger. Private actors like SpaceX and Satellite Mega-Constellations have significantly changed the orbital landscape, launching over 42,000 satellites to provide global internet connection (Marchisio, 2009). However, this expansion raises concerns about collision hazards and orbital congestion. Regulatory bodies like the International Telecommunication Union (ITU) are fighting to manage spectrum distribution during the satellite boom.

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[28] Miraux, L. (2022). Environmental limits to the space sector's growth. Science of The Total Environment, 806, 150862.

[29] Martin, A. S., & Freeland, S. (2021). The advent of artificial intelligence in space activities: New legal challenges. Space Policy, 55, 101408

[30] Palmroth, M., Tapio, J., Soucek, A., Perrels, A., Jah, M., Lönnqvist, M., ... & Virtanen, J. (2021). Toward sustainable use of space: Economic, technological, and legal perspectives. Space Policy, 57, 101428

[31] Wolfrum, R. Die Internationalisierung Staatsfreier Räume; Springer: Berlin/Heidelberg, Germany; New York,NY, USA, 1983; p. 262. ISBN 978-3-642-69481-3

Satellites are crucial for national security, providing military communications, missile detection, and surveillance. Geopolitical rivalry in space is rising as nations send more military satellites into orbit. Space warfare is becoming a serious concern, with satellites as potential targets in future conflicts. Recent geopolitical crises like the Russia-Ukraine conflict have highlighted the strategic value of satellite communications (Schrogl & Neumann, 2009)[32]. However, commercial satellites in conflict areas raise questions about impartiality, sovereignty, and responsibility.

International Legal Frameworks and Regulatory Challenges

Space law, founded mainly in international treaties such as the Outer Space Treaty and various agreements, is challenged by the absence of specific debris mitigation provisions and enforcing methodology. Non-binding existing frameworks like the UN's Space Debris Mitigation Guidelines and IADC recommendations have caused varied implementation. Jurisdictional ambiguities, lack of enforcement mechanisms, and a regulatory lag due to technological advancements pose challenges to AI regulation (Antarctic Treaty, 1961).[33]

Potential for War and Militarization of Space

Since the disturbance of satellites may release millions of pieces of space junk, therefore undermining world communication and defence, ASAT weapon deployment and military satellites presage space battles. Competition between China, the United States, and Russia in furthering lunar exploration and transit to Mars stretches space-based geopolitics to the area around Earth. The Artemis Accords and China-Russia lunar alliance show different alignments; without effective diplomacy, rivalry for space resources and orbital territory might start wars.

More than 30,000 trackable items above 10 cm and 900,000 between 1 and 10 cm will exist as of 2024. Should mega-constellations go unbridled by 2030, the total count of active satellites may surpass 100,000. Over the last ten years, the likelihood of accidents in LEO has increased by 23%; meanwhile, debris avoidance techniques run satellite operators around $500 million annually.

The Kessler Syndrome immediately threatens orbital sustainability as business rivalry and geopolitical struggle for orbital dominance have accelerated trash accumulation (United Nations Convention on the Law of the Sea, 1982)[34]. Sound waste management is based on international collaboration, yet geopolitical rivalry and absence of legally enforceable laws impede advancement. Without robust international agreements, good space traffic management, and debris mitigating technology, Earth's orbital environment may be permanently damaged by the environmental hazards of space rubbish, which are no more theoretical.

4.4 CURRENT INTERNATIONAL RULES AND RECOMMENDATIONS FOR SPACE DEBRIS CONTROL

The rapid growth of space activities due to the technical progress and increased involvement of government and private actors has resulted in an important accumulation of orbital debris. The increasing amount of debris in space presents significant risks, including the potential for collisions with functional satellites, as well as the safety of crewed spaceflight and the long-term viability of activities in space. In light of these risks, the international community has put in place different rules, treaties and guidelines aimed at reducing and managing space debris. Haphazard as these frameworks may be, they are intended

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[32] Schrogl, K.-U.; Neumann, J. Article IV OST. In Cologne Commentary on Space Law; Schmidt-Tedd, H.,Schrogl, K.-U., Eds.; Heymanns Verlag: Cologne, Germany, 2009; Volume 1, p. 90. ISBN 978-3-452-27185-3.40

[33] https://documents.ats.aq/keydocs/vol_1/vol1_2_AT_Antarctic_Treaty_e.pdf

to encourage responsible behaviour and thus the long-term sustainability of outer space, however their enforcement and effectiveness remains a challenge (Hobe & Tronchetti, 2013[35]). This section investigates current international legal frameworks, recommendations, and cooperative efforts for space debris control and highlights areas for improvement.

International Legal Frameworks Governing Space Debris

The Outer Space Treaty (OST) is a key international legislation that establishes guidelines for using space, ensuring all nations have access and are responsible for their actions. It emphasizes worldwide responsibility for damage caused by space objects and their peaceful usage. The Responsibility Convention, established in 1972, focuses more on damage compensation than debris avoidance. Countries are required to register their space objects with the UNOOSA to maintain transparency and identify entities contributing to space debris (Hobe, 2009)[36]. The UN Space Debris Mitigation Guidelines provide non-binding recommendations to minimize debris production, including limiting debris release during nominal operations, minimizing unintentional explosions and collisions, and disposing of spacecraft and upper stages within 25 years of mission end.

The 2019 Long-Term Sustainability (LTS) Guidelines aim to improve safety and sustainability in space operations through comprehensive risk assessment, orbital information interchange, and public-private cooperation for debris reduction. However, the rules are non-binding, making global implementation difficult. Space Traffic Management (STM) programs, initiated by the U.S. Space Command and the European Union, track and control orbital activity, allowing real-time collision warnings and preventing conflicts between nations and commercial operators (Brownlie, 2003)[37]. The absence of a worldwide central agency leads to fragmentation approaches and jurisdictional issues. Governments and commercial companies are developing Active Debris Removal (ADR) technologies, but legal challenges, such as establishing property rights in space junk, persist.

Recommendations and Technical Guidelines by International Organizations

- IADC, established in 1993, focuses on preventing on-orbit breakups, safe disposal of defunct satellites, and collision avoidance.
- IADC's guidelines are voluntary and rely on member states' goodwill.
- ITU regulates orbital slots and radio frequency spectrum for satellites, ensuring equitable access and preventing interference.
- ESA's Code of Conduct for space debris mitigation emphasizes design measures, active debris removal technologies, and data-sharing initiatives.
- ESA's guidelines primarily apply to European operators, limiting global coverage.

4.4. PROPOSED FUNCTIONAL LAWS AND OPERATIONAL APPROACHES FOR SUSTAINABLE OUTER SPACE

With more space junk, more commercial space activity, and more geopolitical conflict, outer space sustainability has become a critical problem. With hundreds of active satellites, ongoing missions, and the expansion of mega-constellations like SpaceX's Starlink and Amazon's Project Kuiper, collision and

[35] United Nations Convention on the Law of the Sea https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

[36] Hobe, S. Outer Space Treaty. In Commentary on Space Law; Schmidt-Tedd, H., Schrogl, K.-U., Eds.; HeymannsVerlag: Cologne, Germany, 2009; Volume 1, p. 35. ISBN 978-3-452-27185-3.36

[37] Brownlie, I. Principles of Public International Law, 6th ed.; Diakonia: Bromma, Sweden, 2003; pp. 6–12. ISBN978-0199260713.34. Jakhu, R. Legal issues relating to the global public interest in outer space. J. Space Law 2006,32, 31–110.35.

environmental damage in Earth's orbital environment has become more threatening. Though they provide basic standards, the present international treaties—including the Liability Convention (1972)[38] and the Outer Space Treaty (1967)—do not include enforceable rules and comprehensive debris control policies (UNOOSA, 2018).[39] Projected functional regulations and operational approaches are desperately needed to allow sustainable usage of outer space as space is progressively becoming available to both state and commercial players.

This section offers doable ideas including legal frameworks, technological fixes, operational rules, international collaboration tools, and legal systems to help to lower space junk, prevent orbital congestion, and promote responsible space conduct.

1. Proposed Functional Laws for Sustainable Outer Space

United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) [40]should draft a legally enforceable worldwide pact on debris mitigating and orbital sustainability.

Key components include mandatory debris mitigating protocols, enforceable post-mission disposal rules, collision responsibility clauses, and routinely occurring compliance audits.

Legislation on Space Traffic Management: Standardized communication protocols, collision avoidance, Global Space Traffic Management Authority (GSTMA)[41] supervision and control of all satellite and debris orbital trajectories, and manoeuvring priority rights establishment (Montrose Environmental Group, 2025).[42]

Legal Foundation for Active Debris Removal (ADR)[43]

- Clear legal rules should address responsibility, consent, and ownership issues in trash disposal.
- Procedures for international organizations removing trash from non-cooperative operators should exist.
- Those that freely remove their space junk might be entitled to priority privileges or tax benefits.

2. Operational Approaches for Sustainable Space Utilization

Effective space debris management depends on technological developments in garbage avoidance. Among them are the creation of satellites and rockets that would break down upon re-entry into the atmosphere, use passive and active debris clearance techniques, and raise space situational awareness (SSA). Among them are ELSA-d Project of Astroscale and ClearSpace-1 Mission of NASA. A Global SSA Database, artificial intelligence collision prediction models, and open-access data rules will help to achieve improved space situational awareness (SSA), which demands exact monitoring and data sharing. To lower

[38] MULTILATERAL Convention on the international liability for damage caused by space objects. Opened for signature at London, Moscow and Washington on 29 March 1972. https://treaties.un.org/doc/Publication/UNTS/Volume%20961/volume-961-I-13810-English.pdf

[39] Idbi 13

[40] Committee on the Peaceful Uses of Outer Space (COPUOS) Input to the High-Level Political Forum in 2022 https://sustainabledevelopment.un.org/index.php?page=view&type=30022&nr=3130&menu=3170

[41] **Global Space Traffic Management Market Insights Forecasts to 2033 https://www.sphericalinsights.com/reports/space-traffic-management-market**

[42] Montrose Environmental Group. (2025, January 31). New Horizons: Brownfields Restoration [Webinar]. Retrieved from https://www.montrose-env.com

[43] Tian, Z. (2024, September 5). Legal aspects of Active Debris Removal (ADR): regulation of ADR under international space law and the way forward for legal development. Meijers-reeks. Retrieved from https://hdl.handle.net/1887/4082461

abandoned spacecraft, demand propellant reserves for controlled deorbiting, and support satellite maintenance missions prolonging operational lives and avoiding waste, end-of-life manoeuvres and satellite servicing must also be included into operational procedures.

5. RESULTS

According to the findings of the study, the number of space junk is growing, and there are already more than 30,000 objects that are bigger than 10 centimetres and can be monitored circling the Earth. The most significant sources include fragmentation events, satellites that have been abandoned, and debris that is still operational. The congestion in orbit has been made worse as a result of geopolitical tensions and economic development by nations and private players like SpaceX. This has increased the likelihood of collisions inside the orbital space. The repercussions of debris put communication networks, global positioning system satellites, and weather satellites in jeopardy, resulting in economic costs that amount to billions of dollars annually. The existing international measures do not include any mechanisms for implementation, and the respect for the United Nations' principles for mitigation is insufficient. Binding conventions, Space Traffic Management systems, and Active Debris Removal all have the potential to be environmentally friendly. The development of technology solutions holds great promise; nevertheless, in order to achieve this, international cooperation and the establishment of well-defined policy frameworks are required.

6. CONCLUSION

A rising accumulation of space debris poses a danger to the viability of Earth's orbital space, which is a challenge to the sustainability of Earth. According to the findings of the research, the risks of accidents, operational danger, and environmental harm have significantly grown as a result of unregulated space activities, geopolitical competition, and economic barriers. Regardless of the worldwide processes that are already in place, the efficacy of these systems has been diminished due to discrepancies in compliance and enforcement.

For the Kessler Syndrome, which is a series of collisions that renders some orbits inaccessible, the adoption of legally binding international regulations, the advancement of technology, and more global cooperation will all be helpful in preventing it. In addition to being a challenge from a technical standpoint, the exploitation of outer space in a manner that is both secure and sustainable requires the collaborative efforts of governments, the corporate sector, and international organizations.

6.1 FUTURE SCOPE

Exploring Space Debris and Its Solutions

- Advanced Debris Removal Technologies: Research on affordable ADR systems like autonomous garbage removers and laser-based platforms.
- Systems for Managing Space Traffic: Development of real-time global STM systems to prevent orbital traffic flow and space collisions.
- Space Situational Awareness Artificial Intelligence: Use of AI and machine learning to enhance collision avoidance and trash detection.
- Study of Policy and Governance: Studying binding legal systems unique to Mega-constellations and private sector involvement.
- Environmental Evaluations: Long-term studies on space operations' and debris re-entry's temperature effects.

- Ethical and Equitable Considerations: Exploring underdeveloped countries' access to orbital resources.

6.2 SUGGESTIONS

Suggestions for Space Debris Sustainability:

- Develop a Binding Global Space Debris Treaty with precise liability provisions, compliance procedures, and penalties.
- Establish a Centralized Global Space Traffic Management Authority overseeing orbital activities and managing mega-constellations.
- Foster Public-Private Partnerships for space debris mitigation technologies.
- Incentivize Responsible Behaviour with financial rewards or orbital priority rights.
- Enact Active Debris Removal Programs and require End-of-Life Plans for Satellites.
- Increase Data Sharing and Transparency through an open-access debris tracking database.
- Prohibit Debris-Generating ASAT Tests and enhance awareness campaigns.
- Regularly update International Guidelines to keep pace with technological developments and operational procedures.

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